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(54) **METHODS AND APPARATUS FOR MULTIPLYING THE IMAGE RESOLUTION AND FIELD-OF-VIEW OF A PIXELATED DISPLAY**

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CPC ***G02B 27/0081*** (2013.01); ***G02B 6/005*** (2013.01); ***G02B 6/0026*** (2013.01); ***G02F 1/2955*** (2013.01); *G02F 2203/24* (2013.01)

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CPC .. G02B 27/0081; G02B 6/0026; G02B 6/005; G02F 1/2955; G02F 2203/24
See application file for complete search history.

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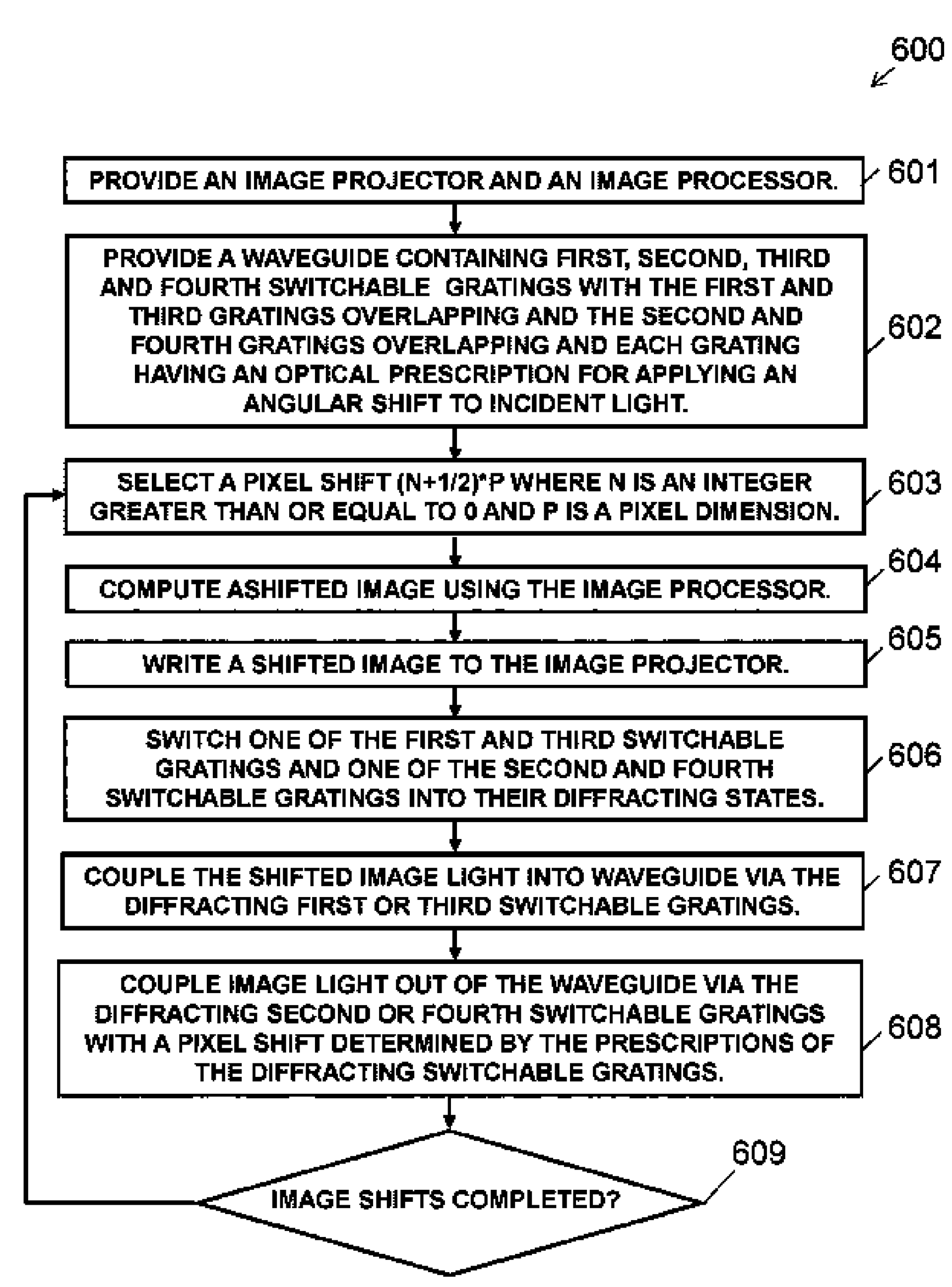
(57) **ABSTRACT**

Systems and methods for multiplying the resolution and field-of-view of pixelated displays in accordance with various embodiments of the invention are illustrated. One embodiment includes an apparatus having an image projector for directing light from a pixelated image source into unique angular directions, an image processor electrically connected to the image projector for computing native images of the image source corresponding to first and second field-of-view portions and for computing shifted images in a predefined direction corresponding to the first and second field-of-view portions for sequential display by the image projector, a first set of gratings having a native configuration for propagating the light of the native image and at least one shifted configuration for propagating the light of at least one shifted image, and a second set of gratings having a first configuration for projecting the first field-of-view portion and a second configuration for projecting the second field-of-view portion.

20 Claims, 11 Drawing Sheets



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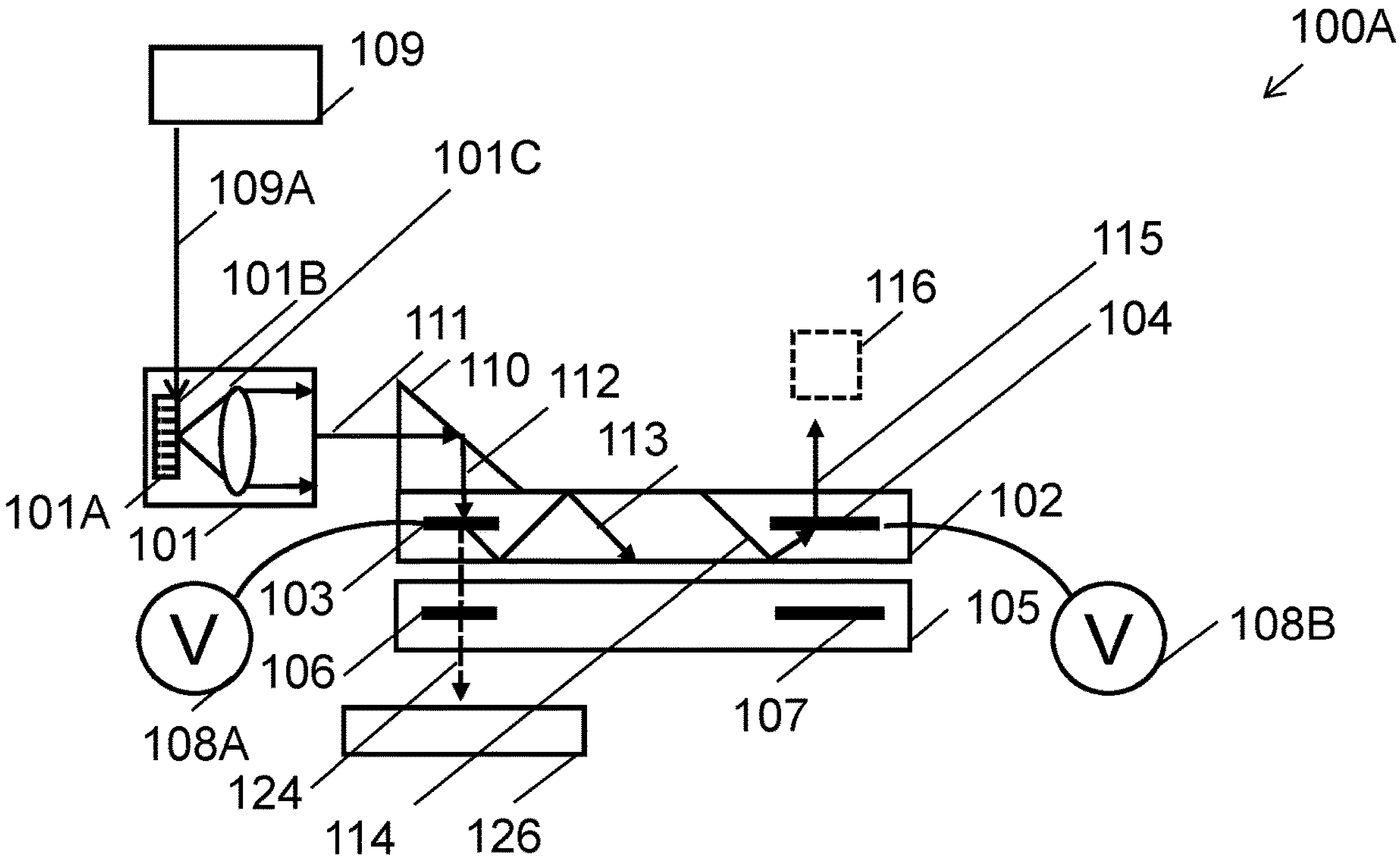
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FIG.1A

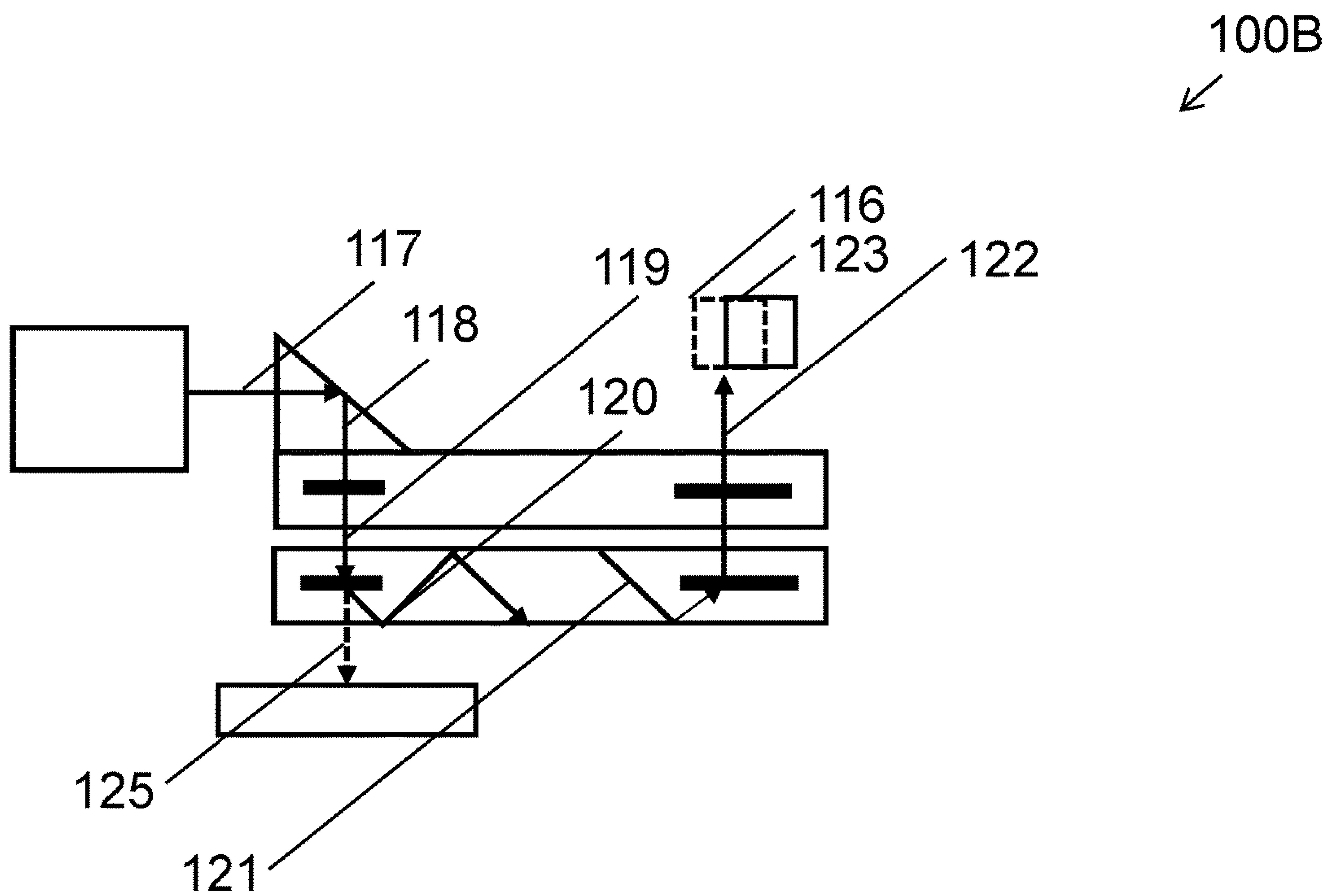
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FIG.1B

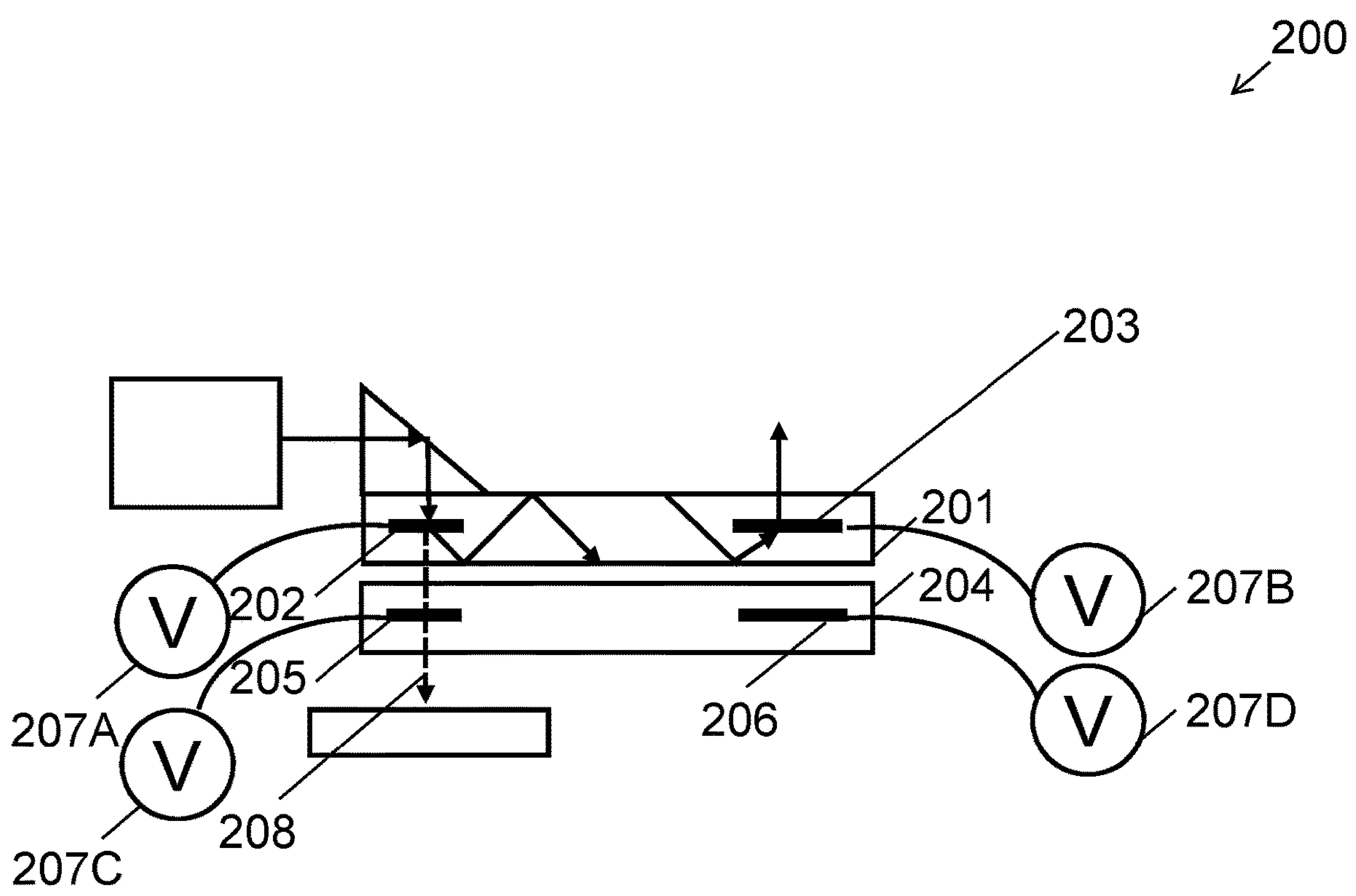
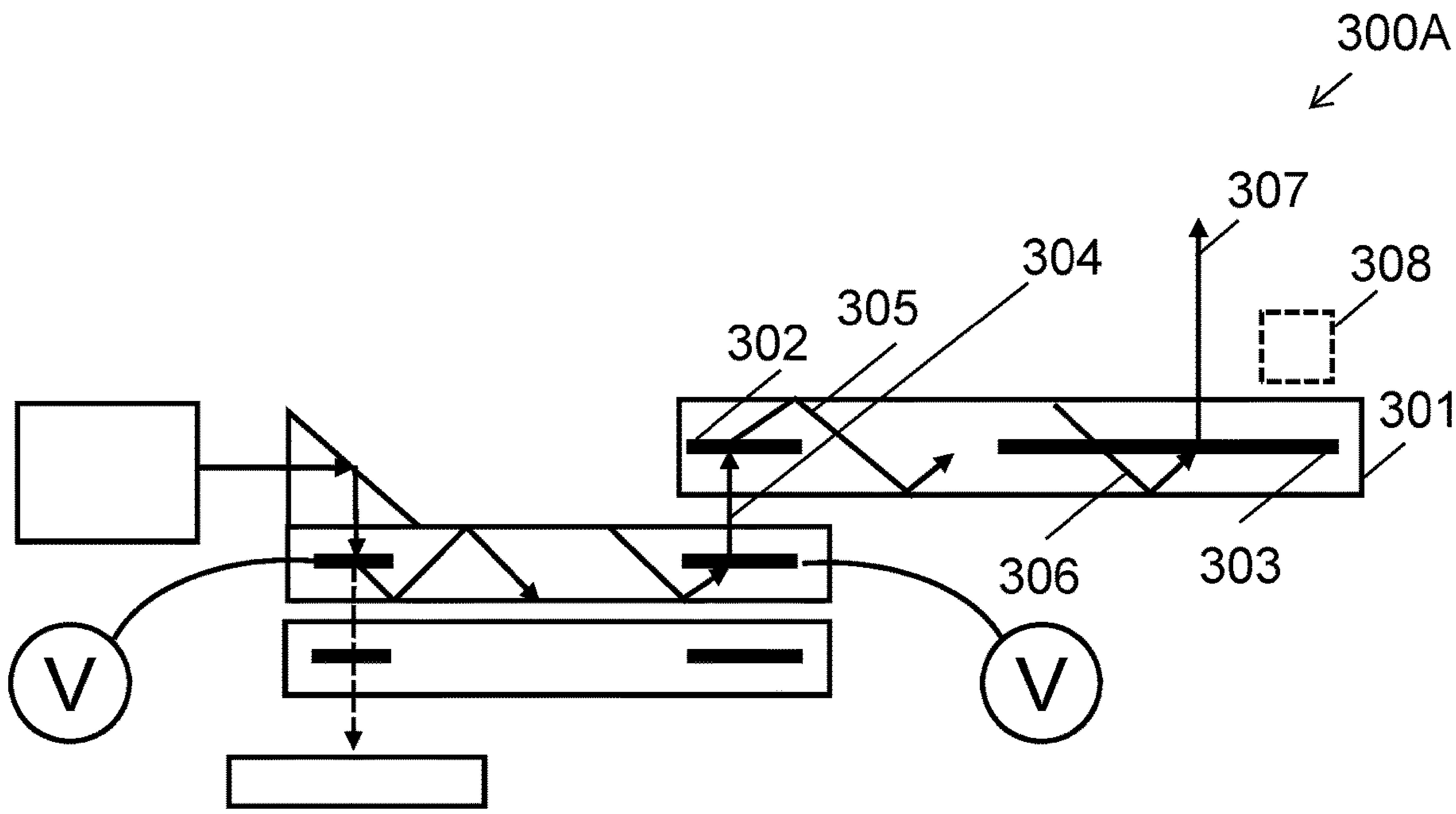


FIG.2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301
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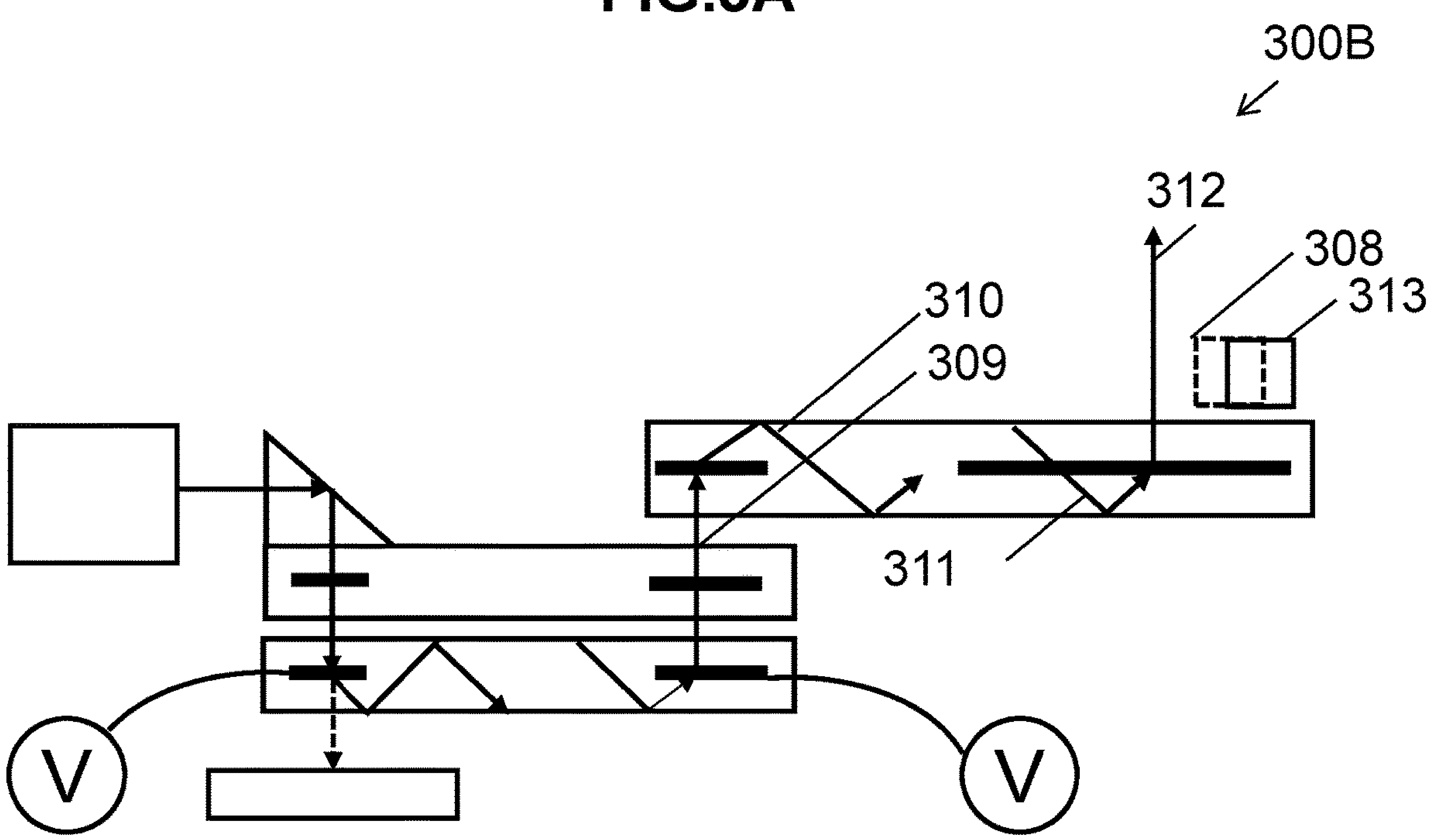
303
V
V

FIG.3A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V

FIG.3B

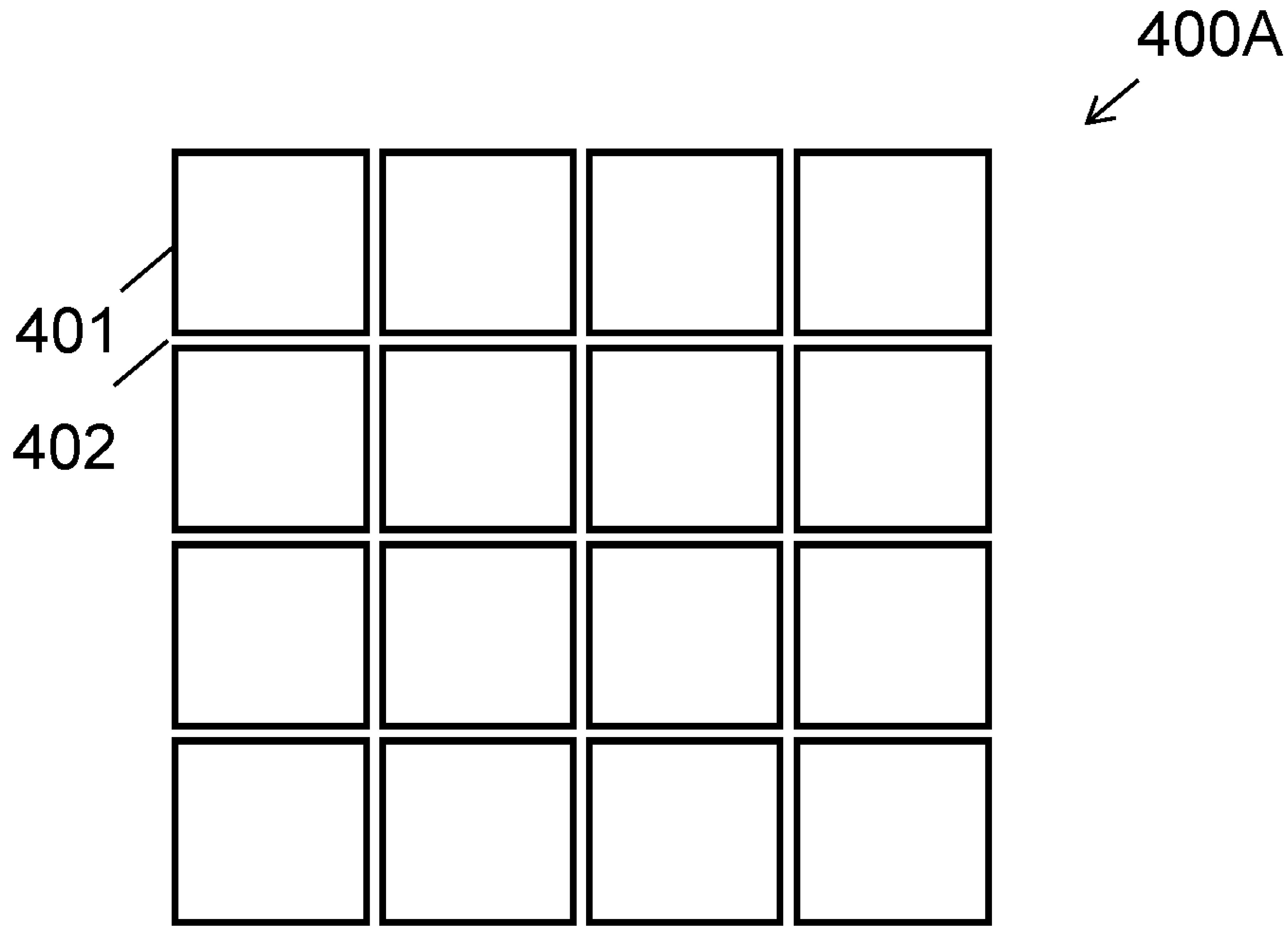


FIG.4A

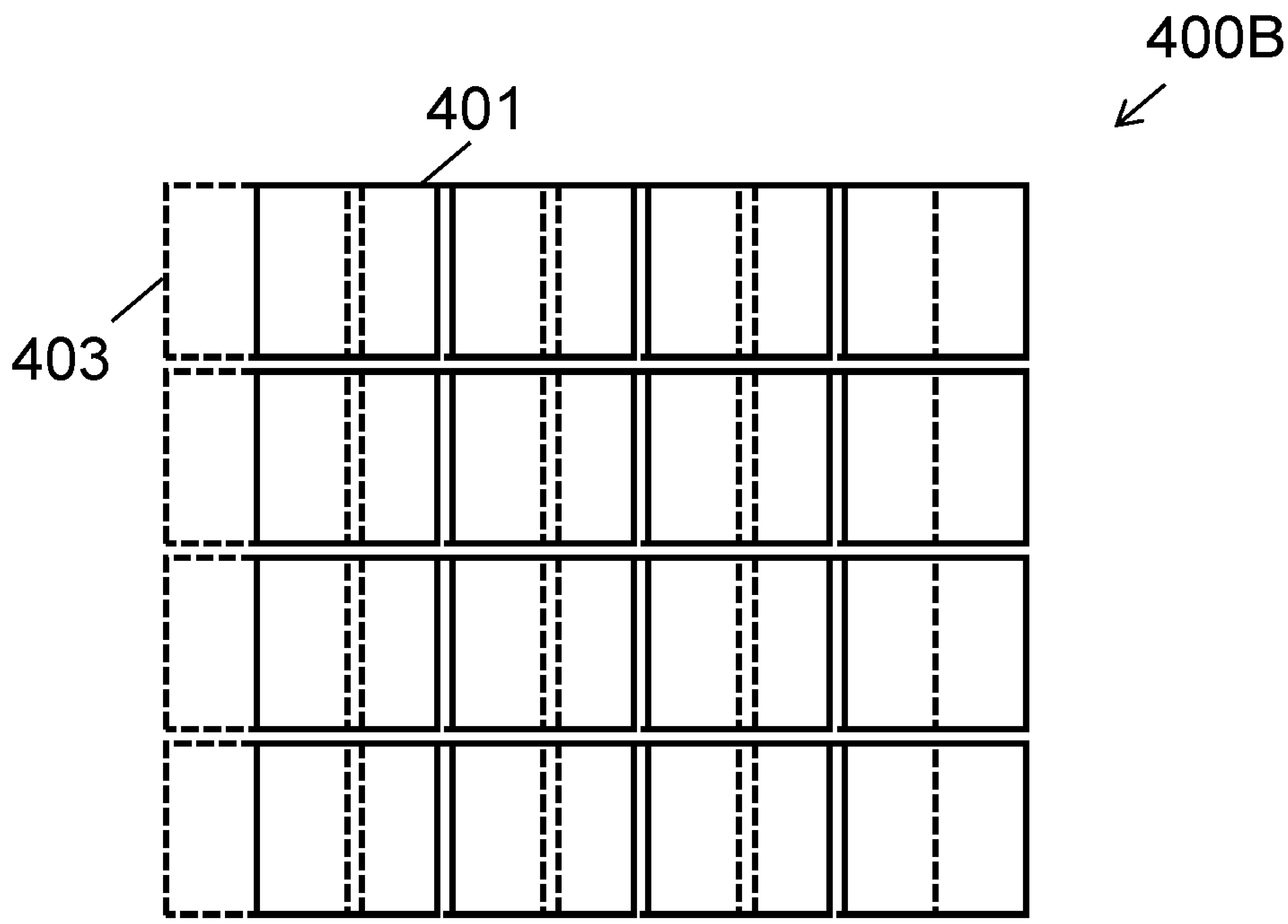


FIG.4B

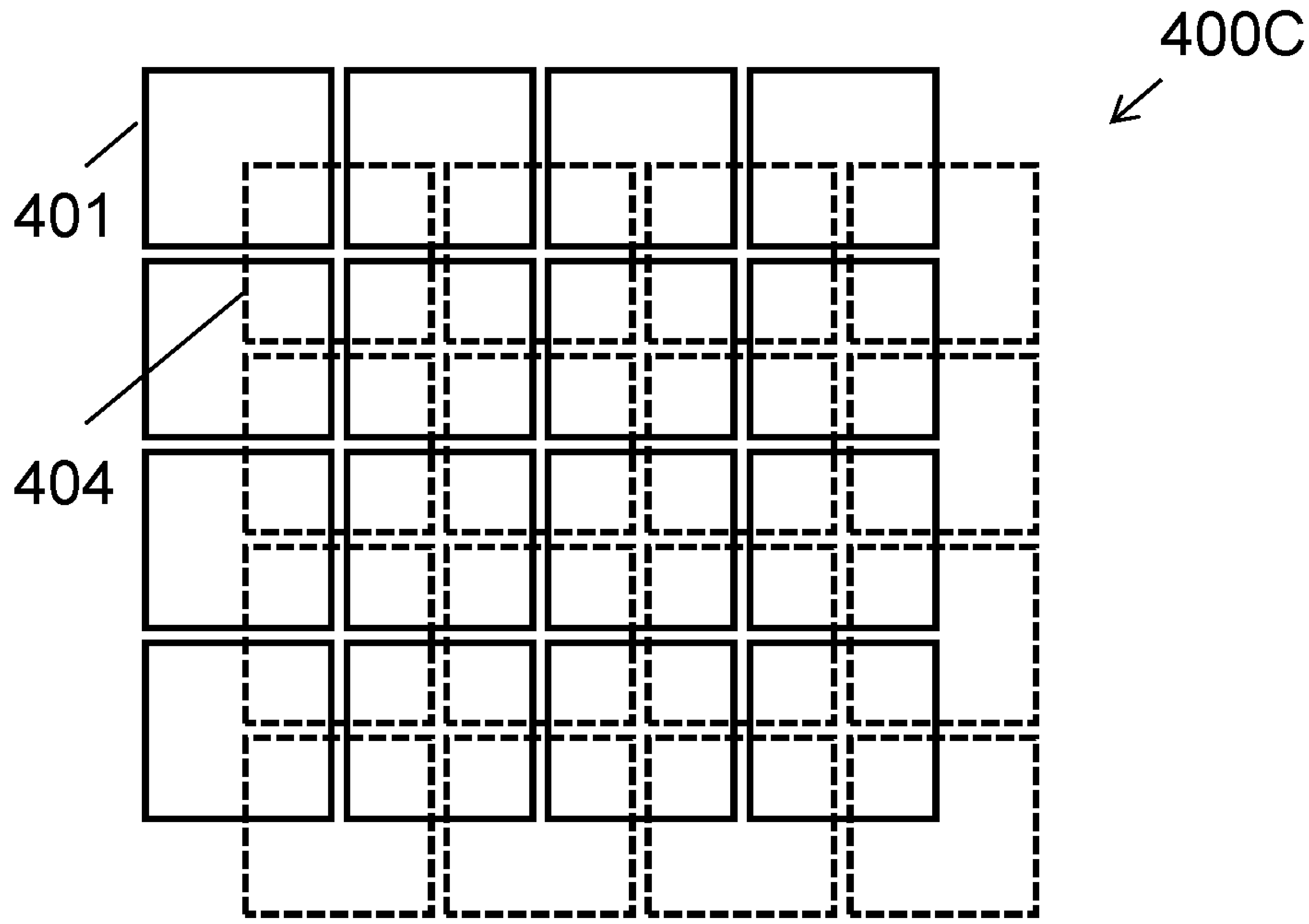


FIG.4C

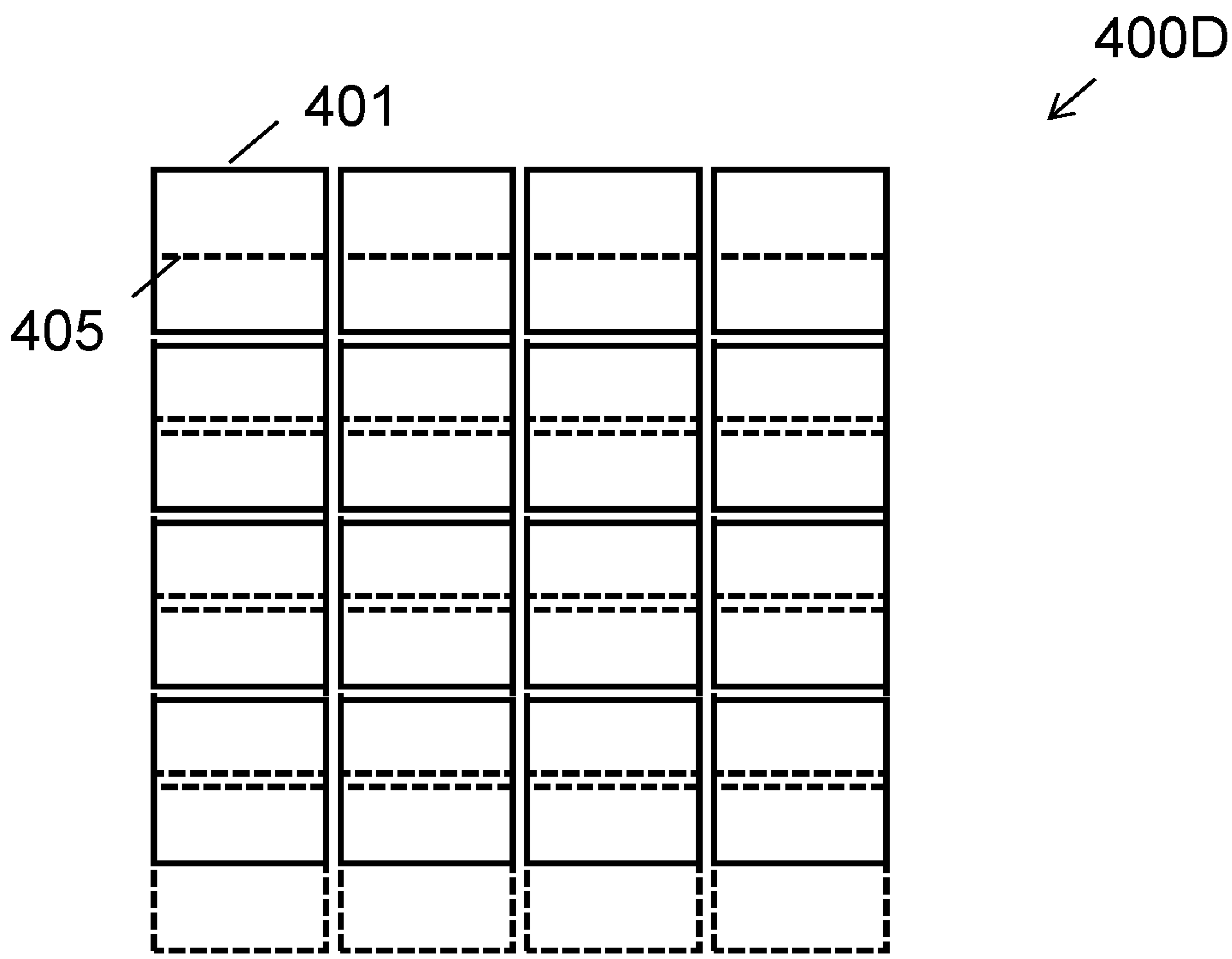
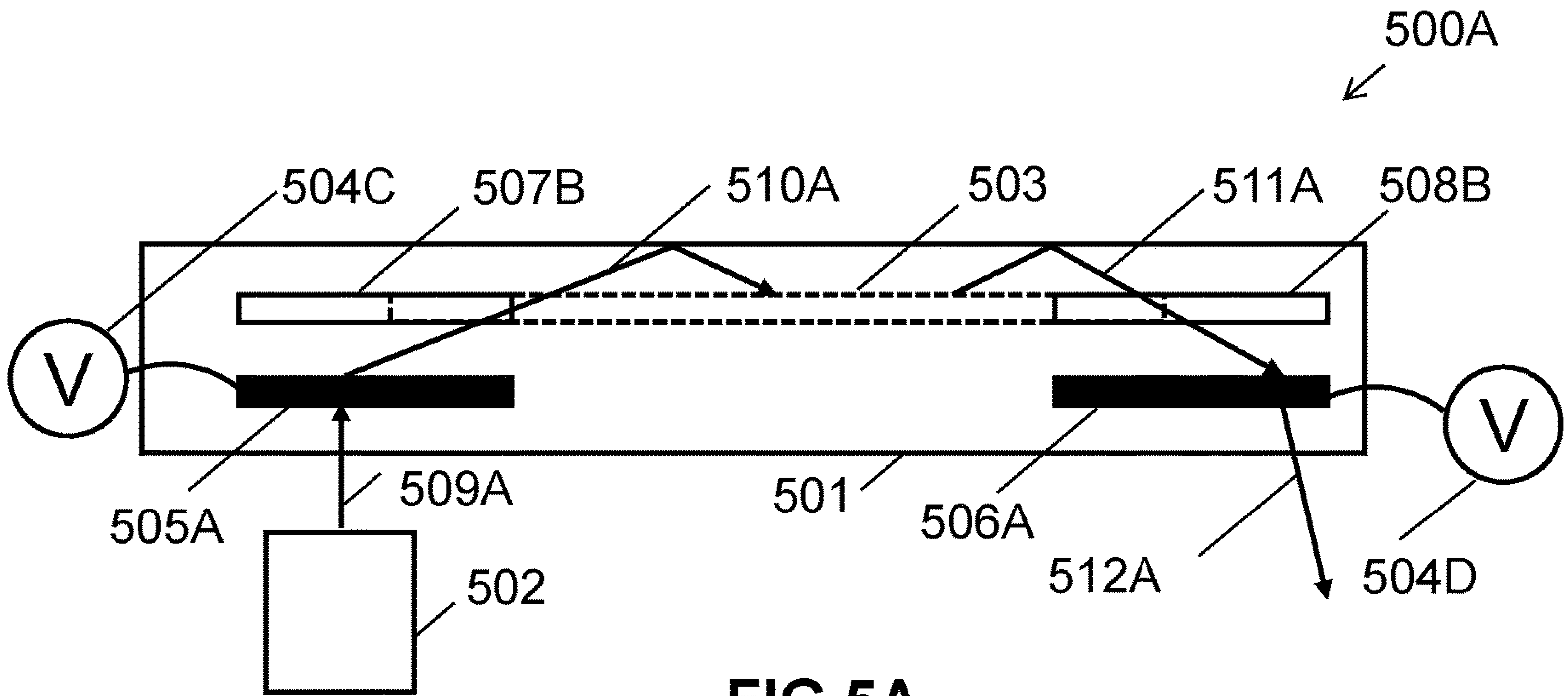


FIG.4D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506A
512A
504D
502

FIG.5A

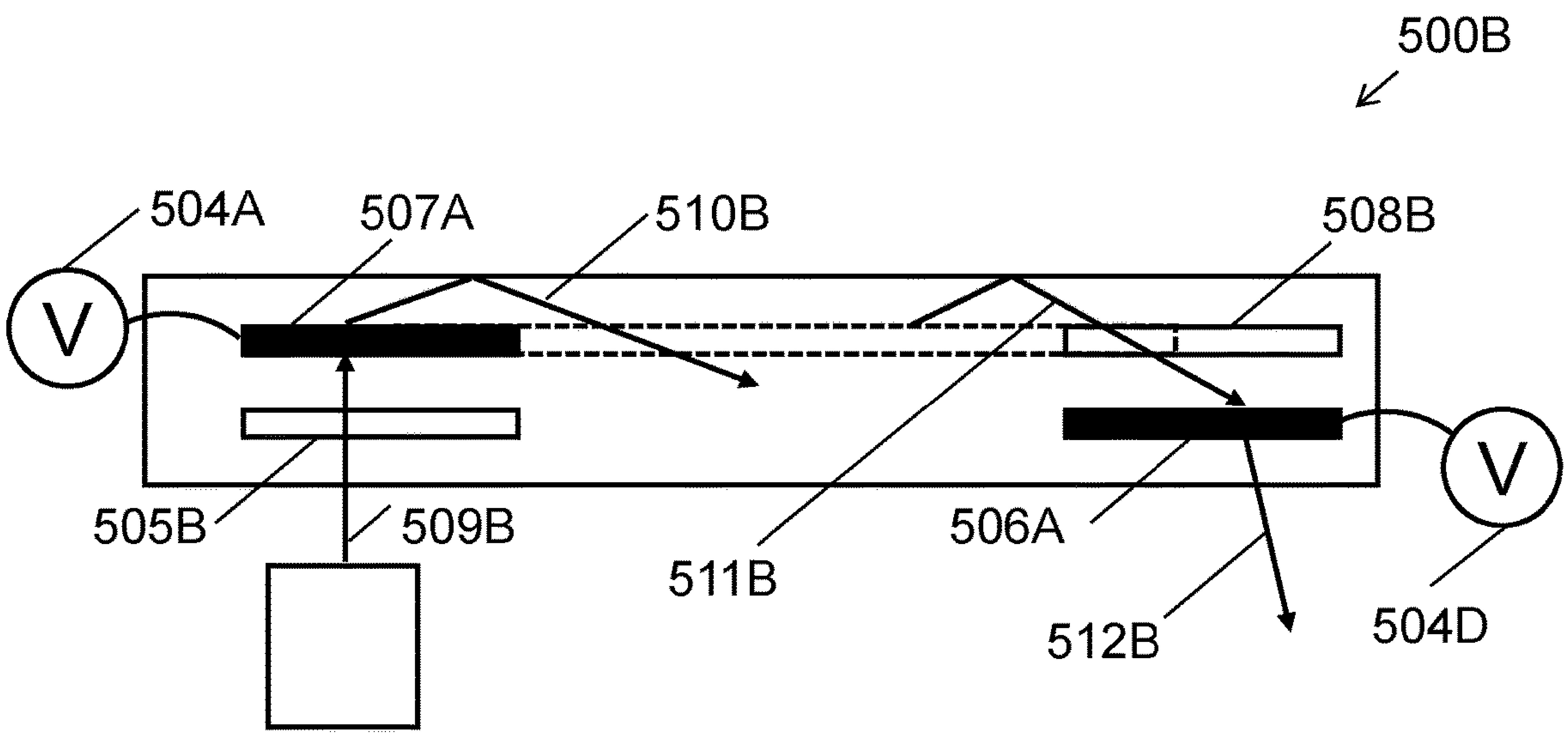
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FIG.5B

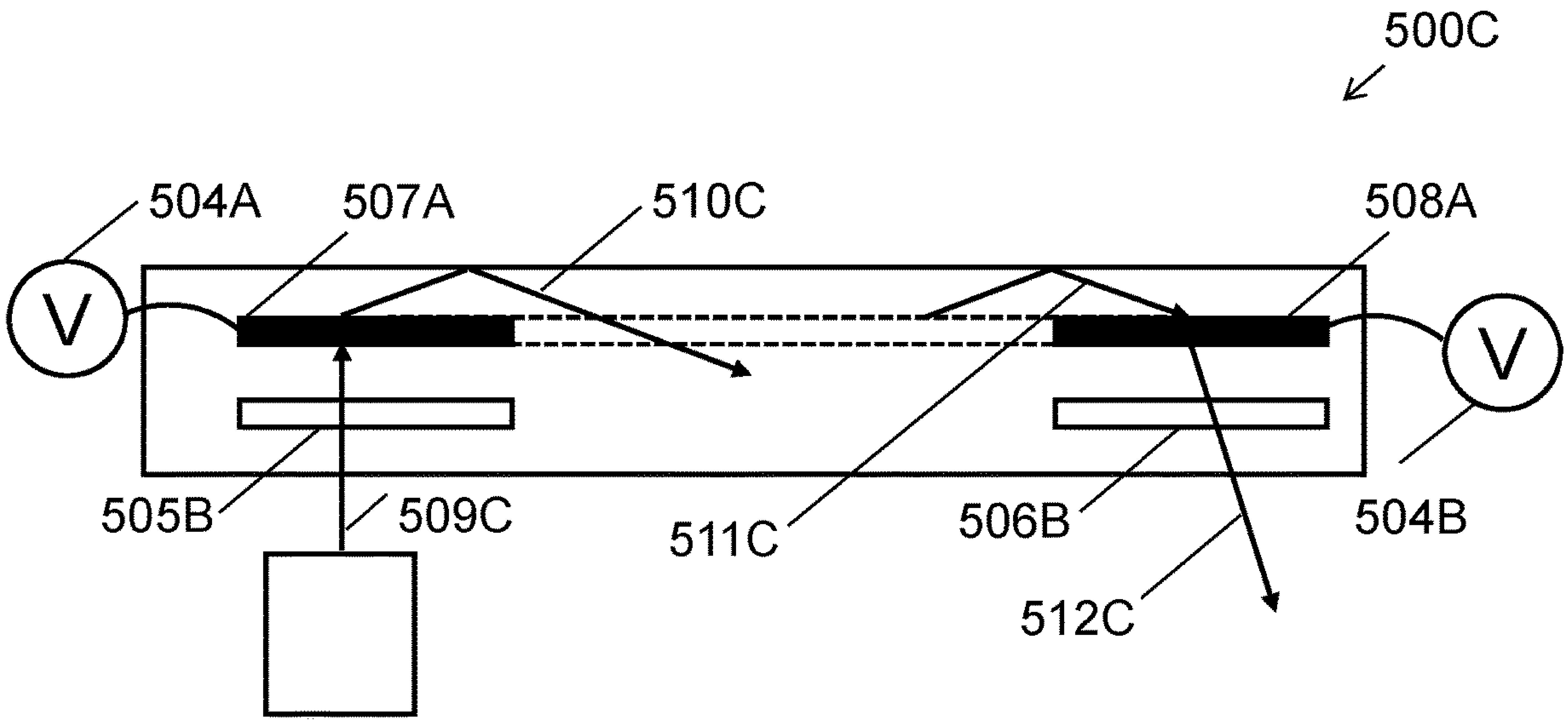
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FIG.5C

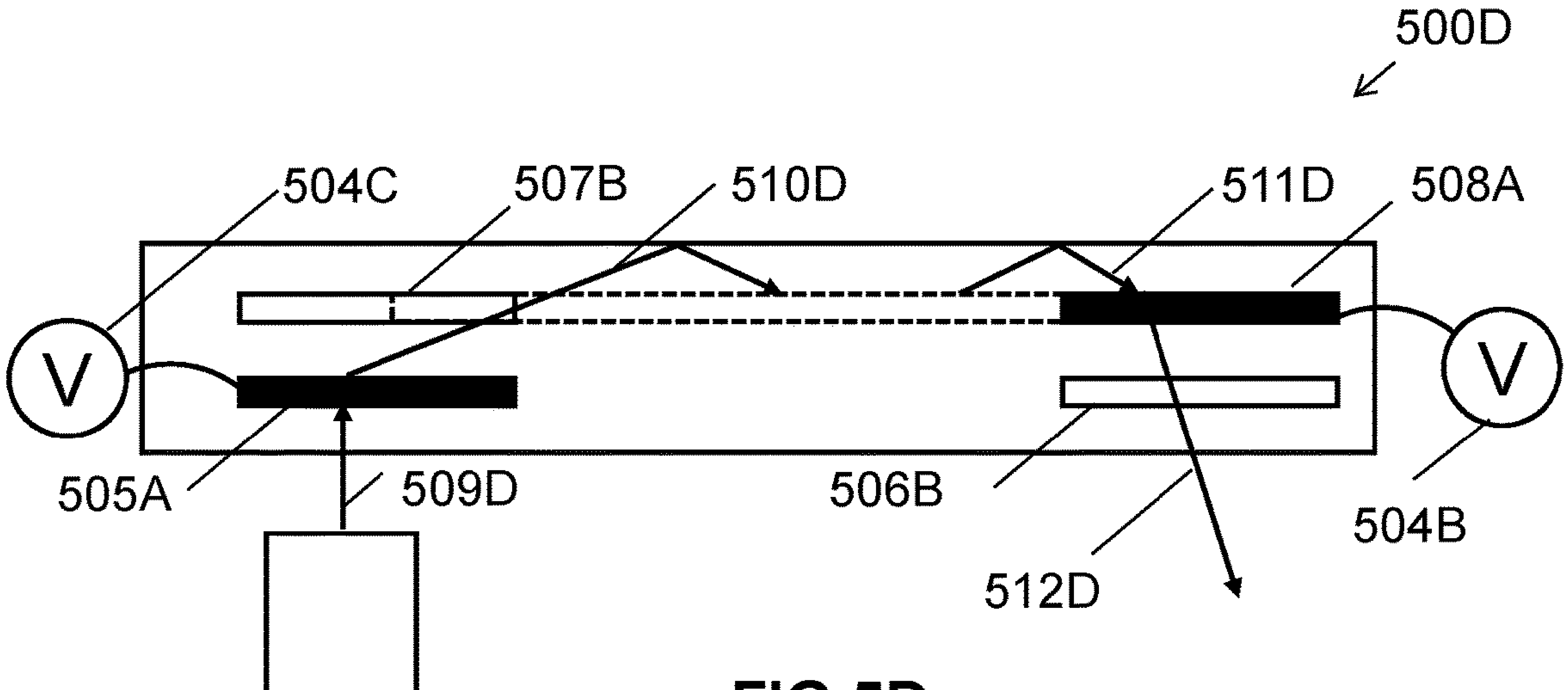
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FIG.5D

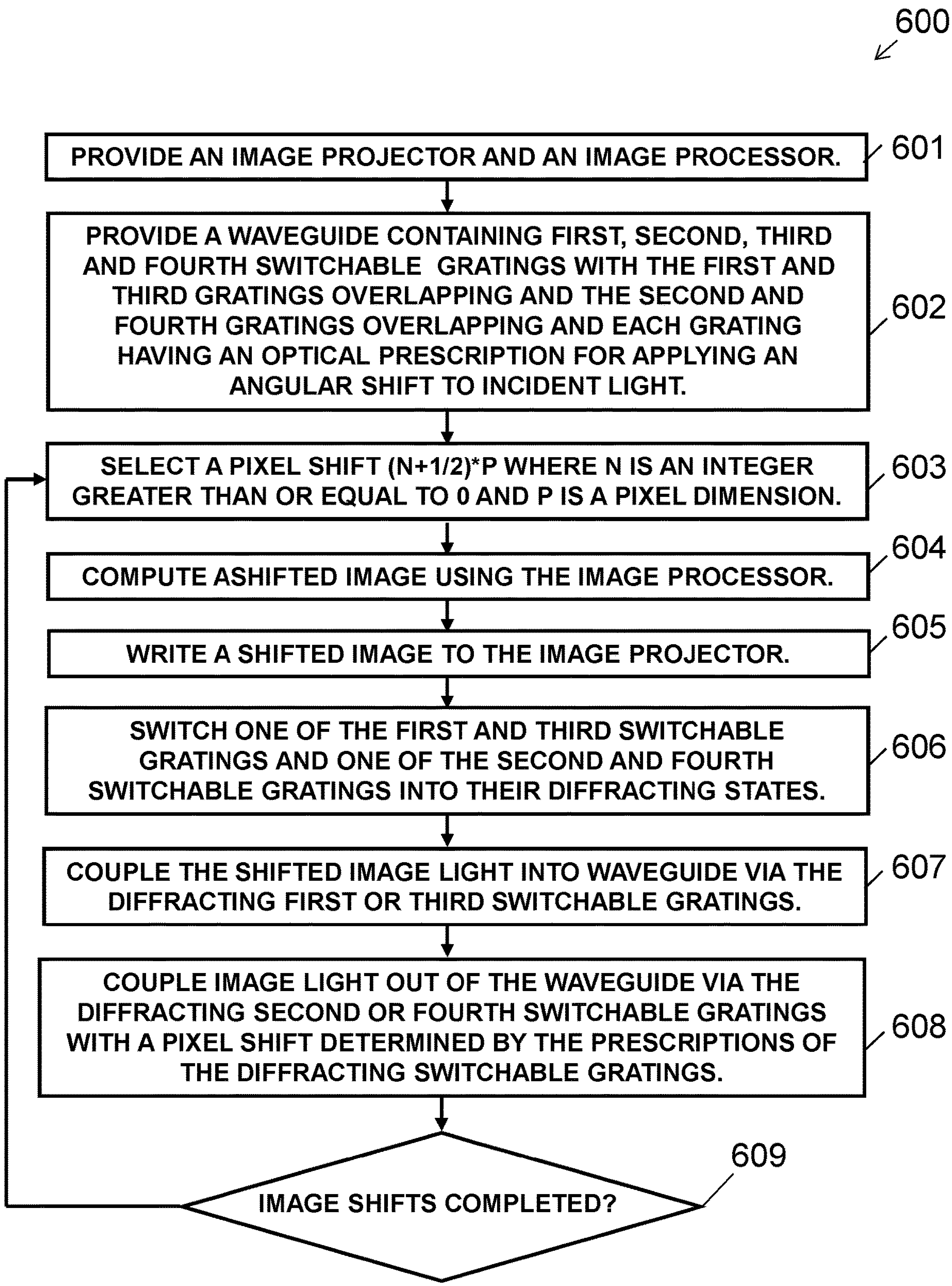
600
PROVIDE AN IMAGE PROJECTOR AND AN IMAGE PROCESSOR.
601
PROVIDE A WAVEGUIDE CONTAINING FIRST, SECOND, THIRD AND FOURTH SWITCHABLE GRATINGS WITH THE FIRST AND THIRD GRATINGS OVERLAPPING AND THE SECOND AND FOURTH GRATINGS OVERLAPPING AND EACH GRATING HAVING AN OPTICAL PRESCRIPTION FOR APPLYING AN ANGULAR SHIFT TO INCIDENT LIGHT.
602
SELECT A PIXEL SHIFT (N+1/2)*P WHERE N IS AN INTEGER GREATER THAN OR EQUAL TO 0 AND P IS A PIXEL DIMENSION.
603
COMPUTE ASHIFTED IMAGE USING THE IMAGE PROCESSOR.
604
WRITE A SHIFTED IMAGE TO THE IMAGE PROJECTOR.
605
SWITCH ONE OF THE FIRST AND THIRD SWITCHABLE GRATINGS AND ONE OF THE SECOND AND FOURTH SWITCHABLE GRATINGS INTO THEIR DIFFRACTING STATES.
606
COUPLE THE SHIFTED IMAGE LIGHT INTO WAVEGUIDE VIA THE DIFFRACTING FIRST OR THIRD SWITCHABLE GRATINGS.
607
COUPLE IMAGE LIGHT OUT OF THE WAVEGUIDE VIA THE DIFFRACTING SECOND OR FOURTH SWITCHABLE GRATINGS WITH A PIXEL SHIFT DETERMINED BY THE PRESCRIPTIONS OF THE DIFFRACTING SWITCHABLE GRATINGS.
608
IMAGE SHIFTS COMPLETED?
609

FIG.6

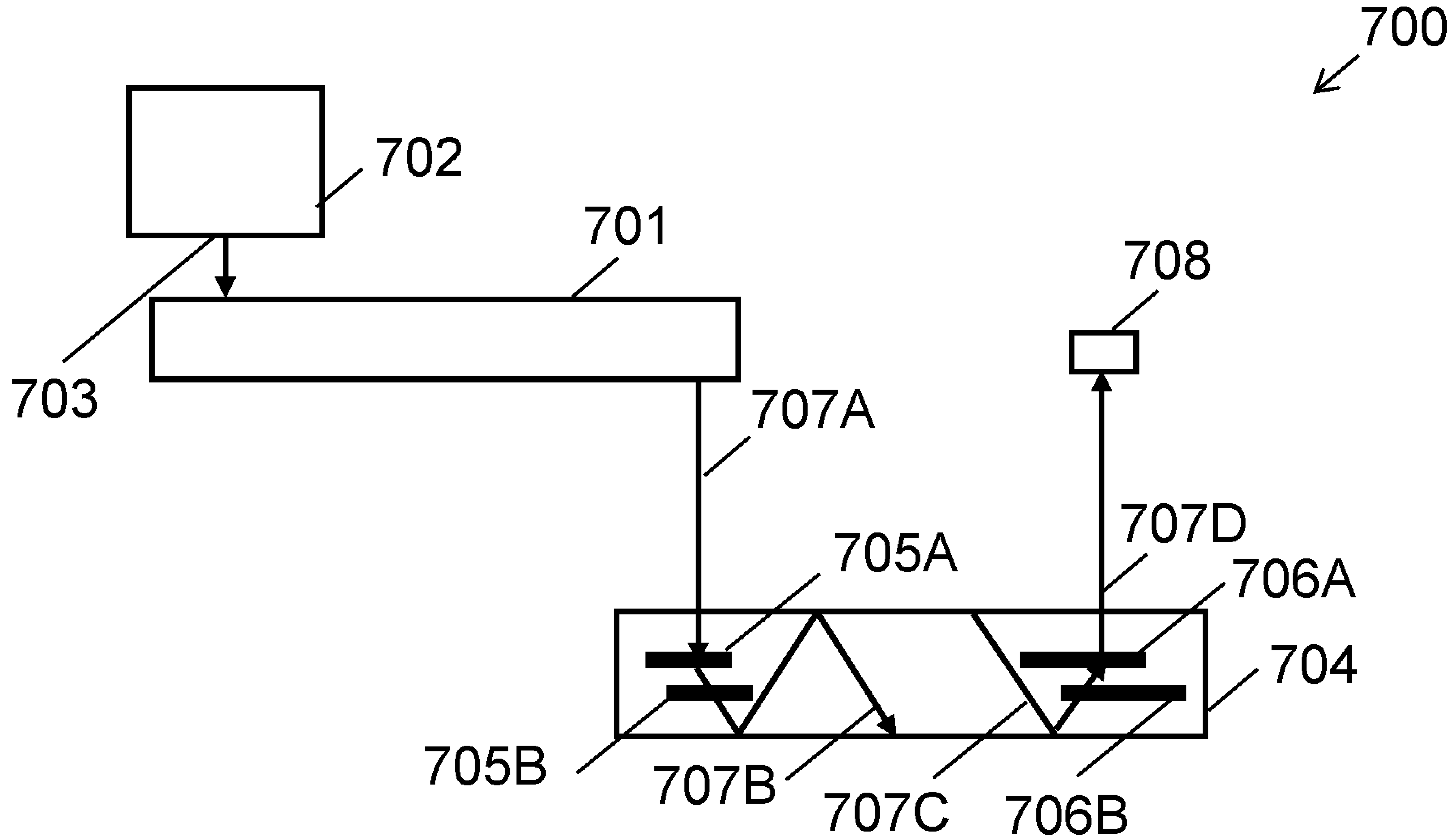
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FIG.7

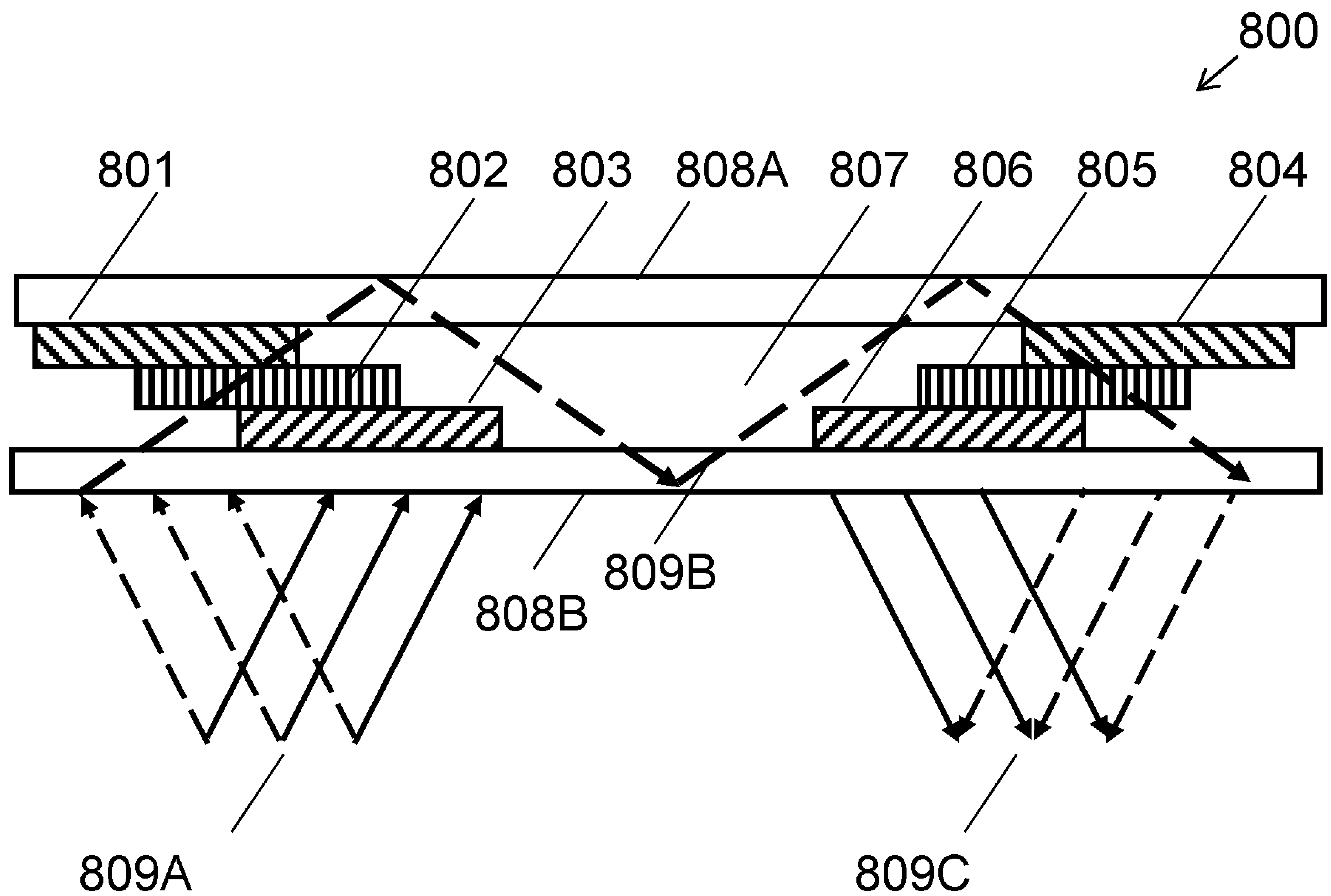
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FIG.8

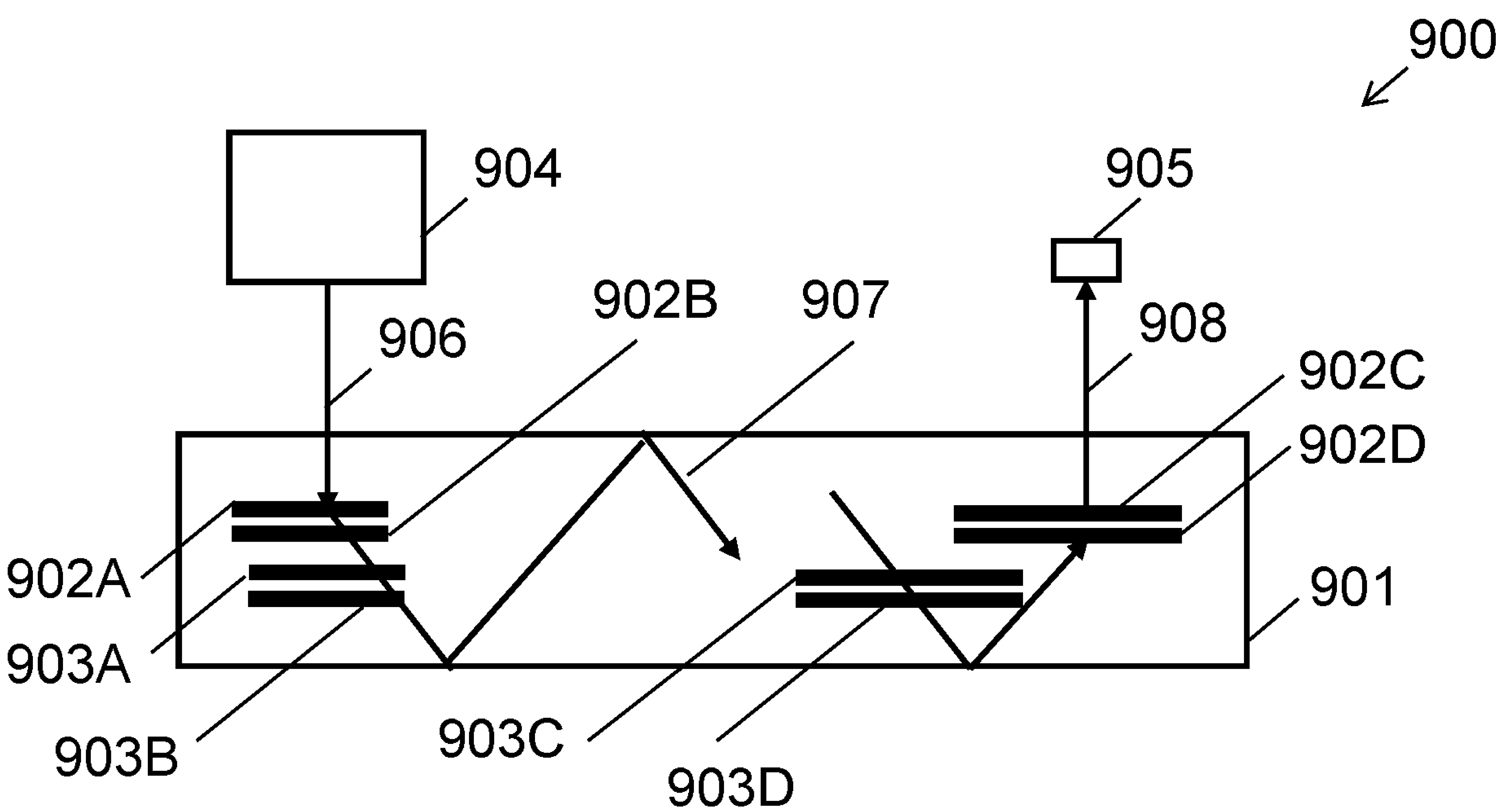
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FIG.9

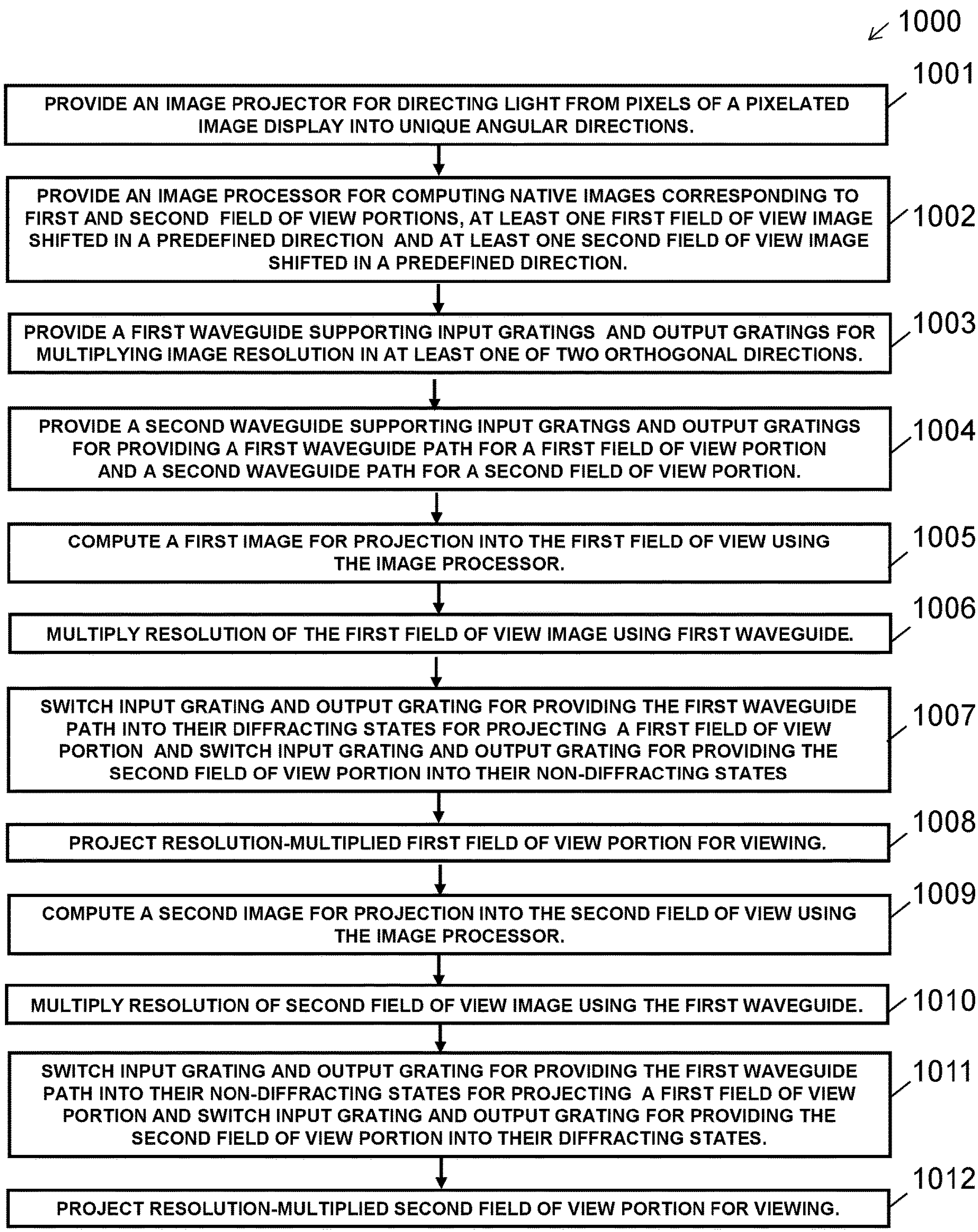
1000
1001
PROVIDE AN IMAGE PROJECTOR FOR DIRECTING LIGHT FROM PIXELS OF A PIXELATED IMAGE DISPLAY INTO UNIQUE ANGULAR DIRECTIONS.
1002
PROVIDE AN IMAGE PROCESSOR FOR COMPUTING NATIVE IMAGES CORRESPONDING TO FIRST AND SECOND FIELD OF VIEW PORTIONS, AT LEAST ONE FIRST FIELD OF VIEW IMAGE SHIFTED IN A PREDEFINED DIRECTION AND AT LEAST ONE SECOND FIELD OF VIEW IMAGE SHIFTED IN A PREDEFINED DIRECTION.
1003
PROVIDE A FIRST WAVEGUIDE SUPPORTING INPUT GRATINGS AND OUTPUT GRATINGS FOR MULTIPLYING IMAGE RESOLUTION IN AT LEAST ONE OF TWO ORTHOGONAL DIRECTIONS.
1004
PROVIDE A SECOND WAVEGUIDE SUPPORTING INPUT GRATNGS AND OUTPUT GRATINGS FOR PROVIDING A FIRST WAVEGUIDE PATH FOR A FIRST FIELD OF VIEW PORTION AND A SECOND WAVEGUIDE PATH FOR A SECOND FIELD OF VIEW PORTION.
1005
COMPUTE A FIRST IMAGE FOR PROJECTION INTO THE FIRST FIELD OF VIEW USING THE IMAGE PROCESSOR.
1006
MULTIPLY RESOLUTION OF THE FIRST FIELD OF VIEW IMAGE USING FIRST WAVEGUIDE.
1007
SWITCH INPUT GRATING AND OUTPUT GRATING FOR PROVIDING THE FIRST WAVEGUIDE PATH INTO THEIR DIFFRACTING STATES FOR PROJECTING A FIRST FIELD OF VIEW PORTION AND SWITCH INPUT GRATING AND OUTPUT GRATING FOR PROVIDING THE SECOND FIELD OF VIEW PORTION INTO THEIR NON-DIFFRACTING STATES
1008
PROJECT RESOLUTION-MULTIPLIED FIRST FIELD OF VIEW PORTION FOR VIEWING.
1009
COMPUTE A SECOND IMAGE FOR PROJECTION INTO THE SECOND FIELD OF VIEW USING THE IMAGE PROCESSOR.
1010
MULTIPLY RESOLUTION OF SECOND FIELD OF VIEW IMAGE USING THE FIRST WAVEGUIDE.
1011
SWITCH INPUT GRATING AND OUTPUT GRATING FOR PROVIDING THE FIRST WAVEGUIDE PATH INTO THEIR NON-DIFFRACTING STATES FOR PROJECTING A FIRST FIELD OF VIEW PORTION AND SWITCH INPUT GRATING AND OUTPUT GRATING FOR PROVIDING THE SECOND FIELD OF VIEW PORTION INTO THEIR DIFFRACTING STATES.
1012
PROJECT RESOLUTION-MULTIPLIED SECOND FIELD OF VIEW PORTION FOR VIEWING.

FIG.10

METHODS AND APPARATUS FOR MULTIPLYING THE IMAGE RESOLUTION AND FIELD-OF-VIEW OF A PIXELATED DISPLAY

CROSS-REFERENCE TO RELATED APPLICATIONS

The current application claims the benefit of and priority under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application No. 62/880,033 entitled "Methods and Apparatus for Multiplying the Image Resolution and Field-of-view of a Pixelated Display," filed Jul. 29, 2019. The disclosure of U.S. Provisional Patent Application No. 62/880,033 is hereby incorporated by reference in its entirety for all purposes.

FIELD OF THE INVENTION

The present disclosure relates to displays and, more particular, to holographic devices for multiplying the resolution and field-of-view of pixelated displays.

BACKGROUND

Waveguides can be referred to as structures with the capability of confining and guiding waves (i.e., restricting the spatial region in which waves can propagate). One subclass includes optical waveguides, which are structures that can guide electromagnetic waves, typically those in the visible spectrum. Waveguide structures can be designed to control the propagation path of waves using a number of different mechanisms. For example, planar waveguides can be designed to utilize diffraction gratings to diffract and couple incident light into the waveguide structure such that the in-coupled light can proceed to travel within the planar structure via total internal reflection (TIR).

Fabrication of waveguides can include the use of material systems that allow for the recording of holographic optical elements within the waveguides. One class of such material includes polymer dispersed liquid crystal (PDLC) mixtures, which are mixtures containing photopolymerizable monomers and liquid crystals. A further subclass of such mixtures includes holographic polymer dispersed liquid crystal (HPDLC) mixtures. Holographic optical elements, such as volume phase gratings, can be recorded in such a liquid mixture by illuminating the material with two mutually coherent laser beams. During the recording process, the monomers polymerize, and the mixture undergoes a photopolymerization-induced phase separation, creating regions densely populated by liquid crystal micro-droplets, interspersed with regions of clear polymer. The alternating liquid crystal-rich and liquid crystal-depleted regions form the fringe planes of the grating. The resulting grating, which is commonly referred to as a switchable Bragg grating (SBG), has all the properties normally associated with volume or Bragg gratings but with much higher refractive index modulation ranges combined with the ability to electrically tune the grating over a continuous range of diffraction efficiency (the proportion of incident light diffracted into a desired direction). The latter can extend from non-diffracting (cleared) to diffracting with close to 100% efficiency.

Waveguide optics, such as those described above, can be considered for a range of display and sensor applications. In many applications, waveguides containing one or more grating layers encoding multiple optical functions can be realized using various waveguide architectures and material systems, enabling new innovations in near-eye displays for augmented reality (AR) and virtual reality (VR), compact head-up displays (HUDs) and helmet-mounted displays or head-mounted displays (HMDs) for road transport, aviation, and military applications, and sensors for biometric and laser radar (LIDAR) applications. Waveguide displays have been proposed that use diffraction gratings to preserve eye box size while reducing lens size. Head-up displays where the pupil of a collimating optical system is effectively expanded by the waveguide structure can also be implemented.

SUMMARY OF THE INVENTION

Systems and methods for multiplying the resolution and field-of-view of pixelated displays in accordance with various embodiments of the invention are illustrated. One embodiment includes an apparatus for multiplying display resolution and field-of-view, the apparatus including an image projector for directing light from pixels of a pixelated image source into unique angular directions wherein the image projector includes a microdisplay panel optically connected to a projection lens, an image processor electrically connected to the image projector for computing native images of the image source corresponding to first and second field-of-view portions and for computing shifted images in a predefined direction corresponding to the first and second field-of-view portions for sequential display by the image projector, a first set of gratings including a first input grating optically coupled to the image projector and a first output grating, wherein the first set of gratings includes at least one switchable grating switchable between a diffracting state and a non-diffracting state, wherein the first set of gratings have a native configuration for propagating the light of the native image and at least one shifted configuration for propagating the light of at least one shifted image, each with an angular displacement corresponding to an image shift in the predefined direction, where the image shift is equal to N+1/M times a pixel dimension, where N and M are integers and N includes zero, and a second set of gratings including a second input grating optically coupled to the first output grating of the first set of gratings, wherein the second set of gratings includes at least one switchable grating switchable between a diffracting state and a non-diffracting state, wherein the second set of gratings have a first configuration for projecting the first field-of-view portion and a second configuration for projecting the second field-of-view portion.

In another embodiment, the first set of gratings is disposed in a first waveguide and the second set of gratings is disposed in a second waveguide.

In a further embodiment, the second set of gratings includes first, second, third, and fourth gratings, wherein the first grating overlaps the third grating and the second grating overlaps the fourth grating, and wherein the first and third gratings act as input couplers and the second and fourth gratings act as output couplers.

In still another embodiment, at least one of the first and third gratings is a switchable grating.

In a still further embodiment, the first, second, third, and fourth gratings are switchable gratings, wherein the first configuration for projecting the first field-of-view portion is provided by one of the first or third switchable gratings and one of the second or fourth switchable gratings in their diffracting states.

In yet another embodiment, the second and fourth gratings are non-switchable gratings.

In a yet further embodiment, the first and second switchable gratings are disposed in a first layer within a waveguide and the third and fourth switchable gratings are disposed in a second layer within the waveguide.

In another additional embodiment, the first and second switchable gratings are disposed in a first waveguide and the third and fourth switchable gratings are disposed in a second waveguide.

In a further additional embodiment, M is equal to 2.

In another embodiment again, the native and the at least one shifted image are sequentially displayed within a human eye integration period.

In a further embodiment again, the image shift includes one of vertical or horizontal shifts.

In still yet another embodiment, the image shift includes vertical and horizontal shifts.

In a still yet further embodiment, the switchable gratings are recorded in a holographic polymer dispersed liquid crystal material.

In still another additional embodiment, the second set of gratings includes a non-switchable grating.

In a still further additional embodiment, the second set of gratings includes a fold grating.

In still another embodiment again, the second set of gratings includes at least one grating multiplexing at least one of wavelength or angular bandwidth.

In a still further embodiment again, the image projector is optically coupled to the first input grating of the first set of gratings by one of a prism or grating.

In yet another additional embodiment, the apparatus further includes an illumination homogenizer.

In a yet further additional embodiment, the second set of gratings includes a rolled k-vector grating.

A yet another embodiment again includes a method of multiplying the resolution and field-of-view of a waveguide display, the method including providing an image projector and an image processor, providing a waveguide display including first and second sets of gratings, wherein each of the first and second sets of gratings includes at least one switchable grating switchable between a diffracting state and a non-diffracting state, wherein the first set of gratings has a native switching configuration and a shifted switching configuration, wherein the second set of grating has a first switching configuration and a second switching configuration, and sequentially projecting at least four images, wherein the at least four images include a native image in a first field-of-view portion, a shifted image in a first field-of-view portion, a native image in a second field-of-view portion, and a shifted image in a second field-of-view portion, wherein the shifted image has an angular displacement with respect to a corresponding native image defined as an image shift that is equal to N+1/M times a pixel dimension, where N and M are integers and N includes zero, wherein the native image in the first field-of-view portion is projected when the first set of gratings is in the native switching configuration and the second set of gratings is in the first switching configuration, the native image in the second field-of-view portion is projected when the first set of gratings is in the native switching configuration and the second set of gratings is in the second switching configuration, the shifted image in the first field-of-view portion is projected when the first set of gratings is in the shifted switching configuration and the second set of gratings is in the first switching configuration, and the shifted image in the second field-of-view portion is projected when the first set of gratings is in the shifted switching configuration and the second set of gratings is in the second switching configuration.

Additional embodiments and features are set forth in part in the description that follows, and in part will become apparent to those skilled in the art upon examination of the specification or may be learned by the practice of the invention. A further understanding of the nature and advantages of the present invention may be realized by reference to the remaining portions of the specification and the drawings, which forms a part of this disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

The description will be more fully understood with reference to the following figures and data graphs, which are presented as exemplary embodiments of the invention and should not be construed as a complete recitation of the scope of the invention.

FIGS. **1**A-**1**B conceptually illustrate schematic cross section views of a resolution multiplication waveguide device in accordance with an embodiment of the invention.

FIG. **2** conceptually illustrates a schematic cross section view of a resolution multiplication waveguide device with two switchable grating layers in accordance with an embodiment of the invention.

FIGS. **3**A-**3**B conceptually illustrate schematic cross section views of a resolution multiplication waveguide device optically interfaced to a waveguide display in accordance with an embodiment of the invention.

FIGS. **4**A-**4**D conceptually illustrate four pixel-shifting steps used to provide resolution quadrupling in accordance with an embodiment of the invention.

FIGS. **5**A-**5**D conceptually illustrate a schematic cross section view of a resolution quadrupling waveguide device in accordance with an embodiment of the invention.

FIG. **6** is a flow chart illustrating a method of multiplying the resolution of a waveguide display in accordance with an embodiment of the invention.

FIG. **7** conceptually illustrates a schematic cross section view of a waveguide apparatus for multiplying the resolution and the field-of-view of a display in accordance with an embodiment of the invention.

FIG. **8** conceptually illustrates a schematic cross section view of a waveguide apparatus for multiplying the field-of-view of a display in accordance with an embodiment of the invention.

FIG. **9** conceptually illustrates a schematic cross section view of a single waveguide for multiplying the resolution and the field-of-view of a display in accordance with an embodiment of the invention.

FIG. **10** is a flow chart illustrating a method of multiplying the resolution and field-of-view of a waveguide display in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

For the purposes of describing embodiments, some well-known features of optical technology known to those skilled in the art of optical design and visual displays have been omitted or simplified in order to not obscure the basic principles of the invention. Unless otherwise stated, the term "on-axis" in relation to a ray or a beam direction refers to propagation parallel to an axis normal to the surfaces of the optical components described in relation to the invention. In the following description the terms light, ray, beam, and direction may be used interchangeably and in association with each other to indicate the direction of propagation of electromagnetic radiation along rectilinear trajectories. The term light and illumination may be used in relation to the visible and infrared bands of the electromagnetic spectrum. Parts of the following description will be presented using terminology commonly employed by those skilled in the art of optical design. As used herein, the term grating may encompass a grating comprised of a set of gratings in some embodiments. For illustrative purposes, it is to be understood that the drawings are not drawn to scale unless stated otherwise.

There is growing consensus that the prerequisite for a successful head mounted AR display is a small, low impact form factor, high brightness, wide field-of-view (FOV) display. A waveguide display can provide a wide FOV by tiling smaller FOVs, with each tile containing imagery formed on a microdisplay coupled to the waveguide. The image content for each FOV tile can be displayed time-sequentially. In general, as FOV increases, it is necessary to provide a high enough resolution to fill the FOV with image detail. To be successful in the market, a 50-degree FOV display should ideally be supported by a resolution of at least 1080p (1920×1080 pixels in 16:9 aspect ratio HD Widescreen standard). U.S. patent application Ser. No. 16/162,280 entitled "Systems and Methods for Multiplying the Image Resolution of a Pixelated Display" filed Oct. 16, 2018 discusses FOV tiling in further detail. The disclosure of U.S. patent application Ser. No. 16/162,280 is hereby incorporated by reference in its entirety for all purposes.

To meet current wearable form factor demands, the microdisplay used to provide the input image should be not greater than 0.23-inches diagonal. However, current pixel sizes do no permit 1080p pixel resolution into a small display area. One way of overcoming the FOV/resolution bottleneck is to use image resolution multiplication. One well established technique pioneered by Texas Instruments (TI) in their rear projection TVs combines their fast switching DLP technology with a high-speed mechanical mirror to enable pixel doubling to 1080p resolution. Such solutions are unsuited for AR wearables, both in terms of form factor and industry resistance to mechanical complexity and cost. Alternative technologies such as organic LED are not mature enough to cost-effectively deliver 1080p resolution with high brightness. As such, there is a requirement for a compact, optically efficiency, and cost-effective solution for display resolution multiplication and FOV multiplication. There is a further requirement for a compact, optically efficient, and cost-effective solution for display resolution multiplication and FOV multiplication integrated within a waveguide display architecture.

Referring generally to the drawings, systems and methods relating to near-eye display or head-up display systems in accordance with various embodiments of the invention are conceptually illustrated. Using the systems and methods disclosed herein, a single optical waveguide substrate can generate a wider field-of-view than found in current and conventional waveguide systems. In many embodiments, diffraction gratings may be used to split and diffract light rays into several beams that travel in different directions, thereby dispersing the light rays. In further embodiments, switchable Bragg gratings (SBGs) can be used in waveguides to eliminate extra layers and to reduce the thickness of current display systems, including HMDs, HUDs, and other near eye displays and to increase the field-of-view by tiling images presented sequentially on a microdisplay. Various types of grating architectures can be implemented for various purposes. In a number of embodiments, a larger exit pupil may be created by using fold gratings in conjunction with conventional gratings (or other types of gratings disclosed herein) to provide pupil expansion on a single waveguide in both the horizontal and vertical directions. Grating structures, waveguide architectures, and display resolution multiplication and FOV multiplication techniques are discussed below in further detail.

Optical Waveguide and Grating Structures

Optical structures recorded in waveguides can include many different types of optical elements, such as but not limited to diffraction gratings. Gratings can be implemented to perform various optical functions, including but not limited to coupling light, directing light, and preventing the transmission of light. In many embodiments, the gratings are surface relief gratings that reside on the outer surface of the waveguide. In other embodiments, the grating implemented is a Bragg grating (also referred to as a volume grating), which are structures having a periodic refractive index modulation. Bragg gratings can be fabricated using a variety of different methods. One process includes interferential exposure of holographic photopolymer materials to form periodic structures. Bragg gratings can have high efficiency with little light being diffracted into higher orders. The relative amount of light in the diffracted and zero order can be varied by controlling the refractive index modulation of the grating, a property that can be used to make lossy waveguide gratings for extracting light over a large pupil.

One class of Bragg gratings used in holographic waveguide devices is the Switchable Bragg Grating (SBG). SBGs can be fabricated by first placing a thin film of a mixture of photopolymerizable monomers and liquid crystal material between substrates. The substrates can be made of various types of materials, such as glass and plastics. In many cases, the substrates are in a parallel configuration. In other embodiments, the substrates form a wedge shape. One or both substrates can support electrodes, typically transparent tin oxide films, for applying an electric field across the film. The grating structure in an SBG can be recorded in the liquid material (often referred to as the syrup) through photopolymerization-induced phase separation using interferential exposure with a spatially periodic intensity modulation. Factors such as but not limited to control of the irradiation intensity, component volume fractions of the materials in the mixture, and exposure temperature can determine the resulting grating morphology and performance. As can readily be appreciated, a wide variety of materials and mixtures can be used depending on the specific requirements of a given application. In many embodiments, HPDLC material is used. During the recording process, the monomers polymerize, and the mixture undergoes a phase separation. The LC molecules aggregate to form discrete or coalesced droplets that are periodically distributed in polymer networks on the scale of optical wavelengths. The alternating liquid crystal-rich and liquid crystal-depleted regions form the fringe planes of the grating, which can produce Bragg diffraction with a strong optical polarization resulting from the orientation ordering of the LC molecules in the droplets.

The resulting volume phase grating can exhibit very high diffraction efficiency, which can be controlled by the magnitude of the electric field applied across the film. When an electric field is applied to the grating via transparent electrodes, the natural orientation of the LC droplets can change, causing the refractive index modulation of the fringes to lower and the hologram diffraction efficiency to drop to very low levels. Typically, the electrodes are configured such that the applied electric field will be perpendicular to the substrates. In a number of embodiments, the electrodes are fabricated from indium tin oxide (ITO). In the OFF state with no electric field applied, the extraordinary axis of the liquid crystals generally aligns normal to the fringes. The grating thus exhibits high refractive index modulation and high diffraction efficiency for P-polarized light. When an electric field is applied to the HPDLC, the grating switches to the ON state wherein the extraordinary axes of the liquid crystal molecules align parallel to the applied field and hence perpendicular to the substrate. In the ON state, the grating exhibits lower refractive index modulation and lower diffraction efficiency for both S- and P-polarized light. Thus, the grating region no longer diffracts light. Each grating region can be divided into a multiplicity of grating elements such as for example a pixel matrix according to the function of the HPDLC device. Typically, the electrode on one substrate surface is uniform and continuous, while electrodes on the opposing substrate surface are patterned in accordance with the multiplicity of selectively switchable grating elements.

Typically, the SBG elements are switched clear in 30 μs with a longer relaxation time to switch ON. The diffraction efficiency of the device can be adjusted, by means of the applied voltage, over a continuous range. In many cases, the device exhibits near 100% efficiency with no voltage applied and essentially zero efficiency with a sufficiently high voltage applied. In certain types of HPDLC devices, magnetic fields can be used to control the LC orientation. In some HPDLC applications, phase separation of the LC material from the polymer can be accomplished to such a degree that no discernible droplet structure results. An SBG can also be used as a passive grating. In this mode, its chief benefit is a uniquely high refractive index modulation. SBGs can be used to provide transmission or reflection gratings for free space applications. SBGs can be implemented as waveguide devices in which the HPDLC forms either the waveguide core or an evanescently coupled layer in proximity to the waveguide. The substrates used to form the HPDLC cell provide a total internal reflection (TIR) light guiding structure. Light can be coupled out of the SBG when the switchable grating diffracts the light at an angle beyond the TIR condition.

In some embodiments, LC can be extracted or evacuated from the SBG to provide an evacuated Bragg grating (EBG). EBGs can be characterized as a surface relief grating (SRG) that has properties very similar to a Bragg grating due to the depth of the SRG structure (which is much greater than that practically achievable using surface etching and other conventional processes commonly used to fabricate SRGs). The LC can be extracted using a variety of different methods, including but not limited to flushing with isopropyl alcohol and solvents. In many embodiments, one of the transparent substrates of the SBG is removed, and the LC is extracted. In further embodiments, the removed substrate is replaced. The SRG can be at least partially backfilled with a material of higher or lower refractive index. Such gratings offer scope for tailoring the efficiency, angular/spectral response, polarization, and other properties to suit various waveguide applications.

Waveguides in accordance with various embodiments of the invention can include various grating configurations designed for specific purposes and functions. In many embodiments, the waveguide is designed to implement a grating configuration capable of preserving eyebox size while reducing lens size by effectively expanding the exit pupil of a collimating optical system. The exit pupil can be defined as a virtual aperture where only the light rays which pass though this virtual aperture can enter the eyes of a user. In some embodiments, the waveguide includes an input grating optically coupled to a light source, a fold grating for providing a first direction beam expansion, and an output grating for providing beam expansion in a second direction, which is typically orthogonal to the first direction, and beam extraction towards the eyebox. Fold gratings can be configured to deflect incident light to continue traveling within a TIR path in the waveguide. As can readily be appreciated, the grating configuration implemented waveguide architectures can depend on the specific requirements of a given application. In some embodiments, the grating configuration includes multiple fold gratings. In several embodiments, the grating configuration includes an input grating and a second grating for performing beam expansion and beam extraction simultaneously. The second grating can include gratings of different prescriptions, for propagating different portions of the field-of-view, arranged in separate overlapping grating layers or multiplexed in a single grating layer. Furthermore, various types of gratings and waveguide architectures can also be utilized.

In several embodiments, the gratings within each layer are designed to have different spectral and/or angular responses. For example, in many embodiments, different gratings across different grating layers are overlapped, or multiplexed, to provide an increase in spectral bandwidth. In some embodiments, a full color waveguide is implemented using three grating layers, each designed to operate in a different spectral band (red, green, and blue). In other embodiments, a full color waveguide is implemented using two grating layers, a red-green grating layer and a green-blue grating layer. As can readily be appreciated, such techniques can be implemented similarly for increasing angular bandwidth operation of the waveguide. In addition to the multiplexing of gratings across different grating layers, multiple gratings can be multiplexed within a single grating layer—i.e., multiple gratings can be superimposed within the same volume. In several embodiments, the waveguide includes at least one grating layer having two or more grating prescriptions multiplexed in the same volume. In further embodiments, the waveguide includes two grating layers, each layer having two grating prescriptions multiplexed in the same volume. Multiplexing two or more grating prescriptions within the same volume can be achieved using various fabrication techniques. In a number of embodiments, a multiplexed master grating is utilized with an exposure configuration to form a multiplexed grating. In many embodiments, a multiplexed grating is fabricated by sequentially exposing an optical recording material layer with two or more configurations of exposure light, where each configuration is designed to form a grating prescription. In some embodiments, a multiplexed grating is fabricated by exposing an optical recording material layer by alternating between or among two or more configurations of exposure light, where each configuration is designed to form a grating prescription. As can readily be appreciated, various techniques, including those well known in the art, can be used as appropriate to fabricate multiplexed gratings.

In many embodiments, the waveguide can incorporate at least one of: angle multiplexed gratings, color multiplexed gratings, fold gratings, dual interaction gratings, rolled K-vector gratings, crossed fold gratings, tessellated gratings, chirped gratings, gratings with spatially varying refractive index modulation, gratings having spatially varying grating thickness, gratings having spatially varying average refractive index, gratings with spatially varying refractive index modulation tensors, and gratings having spatially varying average refractive index tensors. In some embodiments, the waveguide can incorporate at least one of: a half wave plate, a quarter wave plate, an anti-reflection coating, a beam splitting layer, an alignment layer, a photochromic back layer for glare reduction, and louvre films for glare reduction. In several embodiments, the waveguide can support gratings providing separate optical paths for different polarizations. In various embodiments, the waveguide can support gratings providing separate optical paths for different spectral bandwidths. In a number of embodiments, the gratings can be HPDLC gratings, switching gratings recorded in HPDLC (such switchable Bragg Gratings), Bragg gratings recorded in holographic photopolymer, or surface relief gratings. In many embodiments, the waveguide operates in a monochrome band. In some embodiments, the waveguide operates in the green band. In several embodiments, waveguide layers operating in different spectral bands such as red, green, and blue (RGB) can be stacked to provide a three-layer waveguiding structure. In further embodiments, the layers are stacked with air gaps between the waveguide layers. In various embodiments, the waveguide layers operate in broader bands such as blue-green and green-red to provide two-waveguide layer solutions. In other embodiments, the gratings are color multiplexed to reduce the number of grating layers. Various types of gratings can be implemented. In some embodiments, at least one grating in each layer is a switchable grating.

Waveguides incorporating optical structures such as those discussed above can be implemented in a variety of different applications, including but not limited to waveguide displays. In various embodiments, the waveguide display is implemented with an eyebox of greater than 10 mm with an eye relief greater than 25 mm. In some embodiments, the waveguide display includes a waveguide with a thickness between 2.0-5.0 mm. In many embodiments, the waveguide display can provide an image field-of-view of at least 50° diagonal. In further embodiments, the waveguide display can provide an image field-of-view of at least 70° diagonal. The waveguide display can employ many different types of picture generation units (PGUs). In several embodiments, the PGU can be a reflective or transmissive spatial light modulator such as a liquid crystal on Silicon (LCoS) panel or a micro electromechanical system (MEMS) panel. In a number of embodiments, the PGU can be an emissive device such as an organic light emitting diode (OLED) panel. In some embodiments, an OLED display can have a luminance greater than 4000 nits and a resolution of 4 k×4 k pixels. In several embodiments, the waveguide can have an optical efficiency greater than 10% such that a greater than 400 nit image luminance can be provided using an OLED display of luminance 4000 nits. Waveguides implementing P-diffracting gratings (i.e., gratings with high efficiency for P-polarized light) typically have a waveguide efficiency of 5%-6.2%. Since P-diffracting or S-diffracting gratings can waste half of the light from an unpolarized source such as an OLED panel, many embodiments are directed towards waveguides capable of providing both 5-diffracting and P-diffracting gratings to allow for an increase in the efficiency of the waveguide by up to a factor of two. In some embodiments, the S-diffracting and P-diffracting gratings are implemented in separate overlapping grating layers. Alternatively, a single grating can, under certain conditions, provide high efficiency for both p-polarized and s-polarized light. In several embodiments, the waveguide includes Bragg-like gratings produced by extracting LC from HPDLC gratings, such as those described above, to enable high S and P diffraction efficiency over certain wavelength and angle ranges for suitably chosen values of grating thickness (typically, in the range 2-5 μm).

Optical Recording Material Systems

Material systems in accordance with various embodiments of the invention can include photopolymer mixtures capable of forming holographic Bragg gratings. In a number of embodiments, the mixtures are able to form holographic gratings using interferential photolithography. In such cases, the index modulation is created by the varying exposure intensity of the interference pattern. Any of a variety of lithographic techniques, including those described in the sections above and those well-known in the art, can be used. Compared to conventional techniques relying on index changes through photo-reactivity, material systems and techniques in accordance with various embodiments of the invention utilize phase separation processes initiated through interferential exposure. In many embodiments, the photopolymer mixture includes different types of monomers, dyes, photoinitiators, and nanoparticles. Monomers can include but are not limited to vinyls, acrylates, methacrylates, thiols, epoxides, and other reactive groups. In some embodiments, the mixture can include monomers having different refractive indices. In several embodiments, the mixture can include reactive diluents and/or adhesion promoters. As can readily be appreciated, various types of mixtures and compositions can be implemented as appropriate depending on the specific requirements of a given application. In a number of embodiments, the mixture implemented is based on material systems described in U.S. application Ser. No. 16/242,943 entitled "Low Haze Liquid Crystal Materials" filed Jan. 8, 2019, U.S. application Ser. No. 16/242,954 entitled "Liquid Crystal Materials and Formulations" filed Jan. 8, 2019, U.S. application Ser. No. 16/007,932 entitled "Holographic Material Systems and Waveguides Incorporating Low Functionality Monomers" filed Jun. 13, 2018, and U.S. application Ser. No. 16/799,735 entitled "Holographic Polymer Dispersed Liquid Crystal Mixtures with High Diffraction Efficiency and Low Haze" filed Feb. 24, 2020. The disclosures of U.S. application Ser. Nos. 16/242,943, 16/242,954, 16/007,932, and 16/799,735 are hereby incorporated by reference in their entireties for all purposes.

To form holographic gratings, a master grating can be used to direct an exposure beam and to form an interferential pattern onto a layer of uncured photopolymer material to form gratings. The recording process can be performed on a waveguide cell that includes a layer of uncured photopolymer material sandwiched by two transparent substrates, which are typically made of plastic or glass plates. The waveguide cell with the layer of uncured photopolymer material can be formed in many different ways, including but not limited to vacuum filling and printing deposition processes. By exposing the master grating with a recording beam, a portion of the beam will diffract while a portion passes through as zero-order light. The diffracted portion and the zero-order portion can interfere to expose the photopolymer material. The monomers and nanoparticles phase separated to form alternating regions of monomers and nanoparticles corresponding to the interference pattern, effectively forming a volume Bragg grating. In a number of embodiments, two different exposure beams are utilized to form the interference pattern for the desired exposure.

Depending on the application, the type and size of the formed gratings can differ widely. In several embodiments, the nanoparticle-based photopolymer system is implemented to form isotropic gratings. Isotropic gratings can be advantageous in many different waveguide applications.

Anisotropic gratings, such as those formed from traditional HPDLC material systems, can produce a polarization rotation effect on light propagating within the waveguide, resulting in striations and other undesirable artefacts. Waveguides incorporating isotropic gratings can eliminate many of these artefacts, improving light uniformity. In many embodiments, the nanoparticle-based gratings have high diffraction efficiencies for both S- and P-polarized light, which enable more uniform and efficient waveguides compared to typical HPDLC gratings. In some embodiments, the gratings provide diffraction efficiencies of at least ~20% for at least one of S- and P-polarized light. In further embodiments, the gratings provide diffraction efficiencies of at least ~40% for at least one of S- and P-polarized light. As can readily be appreciated, such gratings can be configured with the appropriate polarized response depending on the specific requirements of a given application. For example, in a number of embodiments, the gratings provide at least ~40% diffraction efficiency for S-polarized light to implement a waveguide display with adequate brightness. In further embodiments, the gratings provide at least ~40% diffraction efficiency for S-polarized light and at least ~10% diffraction efficiency for P-polarized light.

Waveguide applications typically utilize subwavelength-sized gratings to enable the desired propagation and control of light within the waveguide. As such, several embodiments of the invention include the use of nanoparticle-based photopolymer material to form gratings having periods of less than ~500 nm. In further embodiments, the gratings have periods of ~300-500 nm. In a number of embodiments, the type of monomers and nanoparticles can be selected to provide a high rate of diffusion during the phase separation process of the grating formation. A high rate of diffusion can facilitate and can be required in some applications for the formation of small gratings. In many embodiments, the gratings are formed to have rolled K-vectors—i.e., the K-vectors of the gratings vary while maintaining a similar period. In addition to different periods and varying K-vectors, the gratings can also be formed to have a specific thickness, which is typically defined by the thickness of the layer of photopolymer material. As can readily be appreciated, the thickness at which the gratings are formed can depend on the specific application. In general, thinner gratings result in lower diffraction efficiencies but higher operating angular bandwidth. In contrast to other conventional material systems, photopolymer material systems in accordance with various embodiments of the invention are capable of providing thin gratings with sufficient diffraction efficiency values for many desired waveguide applications. In many embodiments, the gratings are formed to have a thickness of less than ~5 μm. In further embodiments, the gratings are formed to have a thickness of ~1-3 μm. In several embodiments, the gratings have a varying thickness profile.

The type of components utilized can depend on the specific requirements of a given application. For example, the type of nanoparticle can be selected to have low reactivity with the remaining components (i.e., the nanoparticles are chosen for their non-reactivity to the monomers, dyes, coinitiators, etc. in the material system). In a number of embodiments, zirconium dioxide nanoparticles are utilized. In many applications, waveguide efficiency is of critical importance. In such cases, a nanoparticle having low-absorptive properties can be advantageous. Given the amount of grating interactions within a typical waveguide application, even absorption values considered low in conventional systems can still result in an unacceptable loss of efficiency. For example, typical metallic nanoparticles having high absorptive properties would likely be undesirable for many waveguide applications. As such, in many embodiments, the type of nanoparticles is selected to provide less than 0.1% absorption. In some embodiments, the nanoparticles are non-metallic. In addition to low absorptive values, other characteristics affecting waveguide performance and grating-formation can also be considered.

Small gratings can be advantageous in many waveguide applications. Compared to traditional HPDLC material systems, phase-separated nanoparticle-based photopolymer material can allow for the formation of gratings with a much higher resolution due to the relatively small size of nanoparticles compared to LC droplets. In typical HPDLC material systems, the LC droplets are about 100 nm in size. This can lead to certain limitations in some applications. For instance, many waveguide applications implement a holographic exposure/recording process for forming gratings within a waveguide. Depending on the application, the resolution of feature sizes of the master grating can be limited. In several embodiments, the master grating has about ~125 nm resolution. As such, forming gratings using 100 nm LC droplets can be difficult and leaves little margin for error. Contrasted with photopolymer material systems described herein, the nanoparticles that form the gratings are at least an order of magnitude smaller. In some embodiments, the material system includes nanoparticles that have diameters of less than 15 nm. In further embodiments, the nanoparticles have diameters of ~4-~10 nm. The relatively small sizes of the nanoparticles in comparison with the resolution of the feature sizes of the master grating allow for the formation of gratings with high fidelity. Furthermore, the physical characteristics of the nanoparticles can allow for the formation of gratings that result in relatively low haze compared to the large liquid crystal droplet sizes of traditional HPDLC material systems. In several embodiments, haze of less than ~1% can be achieved. In further embodiments, the system has haze of less than ~0.5%. Another important characteristic to consider in the selection of the type of nanoparticles to be used includes their refractive indices. In many applications, such as waveguide display applications, the refractive indices of the components and materials can have a large effect on waveguide performance and efficiency. For example, the refractive indices of the components within a grating can determine its diffraction efficiency. In some embodiments, nanoparticles having a high refractive index n are utilized to form gratings having high diffraction efficiencies. For example, in a number of embodiments, ZrO_2 nanoparticles having a refractive index of at least 1.7 are utilized. In some embodiments, nanoparticles having refractive indices of at least 1.9 are utilized. In further embodiments, nanoparticles having refractive indices of at least 2.1 are utilized. The nanoparticles and monomers within the photopolymer mixture are chosen to provide gratings having a high Δn. In several embodiments, the gratings have refractive index modulations of at least ~0.04 Δn. In further embodiments, gratings having refractive index modulations of ~0.05-0.06 Δn are utilized. Such materials can be advantageous in enabling the formation of thin gratings having sufficient diffraction efficiencies for certain waveguide applications. In a number of embodiments, the materials can form ~2 μm-thick gratings having diffraction efficiencies of above 30%. In further embodiments, the gratings can have diffraction efficiencies of above 40%. In certain cases, metallic nanoparticles can be implemented to provide a high refractive index, a typically characteristic of metallic components. However, metallic components typically have high absorption and are unsuitable for use in many different waveguide applications. As such, many embodiments of the invention are directed towards material systems having non-metallic nanoparticles that are capable of forming thin, efficient gratings.

In many embodiments, the material system is an HPDLC mixture. HPDLC mixtures generally include LC, monomers, photoinitiator dyes, and coinitiators. The mixture (often referred to as syrup) frequently also includes a surfactant. For the purposes of describing the invention, a surfactant is defined as any chemical agent that lowers the surface tension of the total liquid mixture. The use of surfactants in PDLC mixtures is known and dates back to the earliest investigations of PDLCs. For example, a paper by R. L Sutherland et al., SPIE Vol. 2689, 158-169, 1996, the disclosure of which is incorporated herein by reference, describes a PDLC mixture including a monomer, photoinitiator, coinitiator, chain extender, and LCs to which a surfactant can be added. Surfactants are also mentioned in a paper by Natarajan et al, Journal of Nonlinear Optical Physics and Materials, Vol. 5 No. I 89-98, 1996, the disclosure of which is incorporated herein by reference. Furthermore, U.S. Pat. No. 7,018,563 by Sutherland; et al., discusses polymer-dispersed liquid crystal material for forming a polymer-dispersed liquid crystal optical element having: at least one acrylic acid monomer; at least one type of liquid crystal material; a photoinitiator dye; a coinitiator; and a surfactant. The disclosure of U.S. Pat. No. 7,018,563 is hereby incorporated by reference in its entirety.

The patent and scientific literature contains many examples of material systems and processes that can be used to fabricate SBGs, including investigations into formulating such material systems for achieving high diffraction efficiency, fast response time, low drive voltage, and so forth. U.S. Pat. No. 5,942,157 by Sutherland, and U.S. Pat. No. 5,751,452 by Tanaka et al. both describe monomer and liquid crystal material combinations suitable for fabricating SBG devices. Examples of recipes can also be found in papers dating back to the early 1990s. Many of these materials use acrylate monomers, including:

R. L. Sutherland et al., Chem. Mater. 5, 1533 (1993), the disclosure of which is incorporated herein by reference, describes the use of acrylate polymers and surfactants. Specifically, the recipe comprises a crosslinking multifunctional acrylate monomer; a chain extender N-vinyl pyrrolidinone, LC E7, photoinitiator rose Bengal, and coinitiator N-phenyl glycine. Surfactant octanoic acid was added in certain variants.

Fontecchio et al., SID 00 Digest 774-776, 2000, the disclosure of which is incorporated herein by reference, describes a UV curable HPDLC for reflective display applications including a multi-functional acrylate monomer, LC, a photoinitiator, a coinitiators, and a chain terminator.

Y. H. Cho, et al., Polymer International, 48, 1085-1090, 1999, the disclosure of which is incorporated herein by reference, discloses HPDLC recipes including acrylates.

Karasawa et al., Japanese Journal of Applied Physics, Vol. 36, 6388-6392, 1997, the disclosure of which is incorporated herein by reference, describes acrylates of various functional orders.

T. J. Bunning et al., Polymer Science: Part B: Polymer Physics, Vol. 35, 2825-2833, 1997, the disclosure of which is incorporated herein by reference, also describes multifunctional acrylate monomers.

G. S. Iannacchione et al., Europhysics Letters Vol. 36 (6). 425-430, 1996, the disclosure of which is incorporated herein by reference, describes a PDLC mixture including a penta-acrylate monomer, LC, chain extender, coinitiators, and photoinitiator.

Acrylates offer the benefits of fast kinetics, good mixing with other materials, and compatibility with film forming processes. Since acrylates are cross-linked, they tend to be mechanically robust and flexible. For example, urethane acrylates of functionality 2 (di) and 3 (tri) have been used extensively for HPDLC technology. Higher functionality materials such as penta and hex functional stems have also been used.

Waveguide Architectures for Resolution Multiplication and FOV Multiplication

In many embodiments, an apparatus for multiplying display resolution can include: an image projector for projecting image light from a microdisplay such that each light from a pixel is mapped into a unique angular direction; an image processor for computing a native image and at least one image shifted in a predefined direction for sequential display by the image projector; and at least one switchable grating switchable between diffracting and non-diffracting states optically coupled to the image processor, or generator, the switchable gratings having a first configuration for propagating the native image light and at least one configuration for propagating the shifted image light with an angular displacement corresponding to the image shift in the direction. In several embodiments, the switchable gratings may be configured in free space. In some embodiments, the switchable gratings are disposed within at least one waveguide.

The image shift can be implemented in several different ways. In a number of embodiments, the image shift is one of vertical or horizontal to provide resolution doubling. In several embodiments, the image shifts include vertical and horizontal shifts to provide doubling of both vertical and horizontal resolutions. In many embodiments, the image shift is equal to exactly half a pixel in the vertical or horizontal dimension. In some embodiments, the image shift is N+½ times a pixel dimension, where N is an integer (where 0 is assumed to be an integer). Such configurations can give more flexibility in the offset design, losing only N pixels in image size. As can readily be appreciated, the image shift can be implemented in a number of different ways. In some embodiments, the image shift can be of any sub-pixel size, such as but not limited to ⅓ or ⅖ times a pixel dimension. In a number of embodiments, the image shift is N+ any fraction of a pixel, where N is an integer. In many embodiments, integer vertical and half pixel horizontal offsets are provided. In some embodiments, integer horizontal and half pixel vertical offsets are provided. In several embodiments, vertical and horizontal offsets have different integer multiples of the pixel dimension to compensate for image offsets arising from non-orthogonal input, fold, and output grating vector (K-vector components) in the plane of a waveguide. In various embodiments, the native and shifted images are sequentially displayed within a human eye integration period.

In many embodiments, a resolution multiplication waveguide can include a set of switchable gratings. In further embodiments, the switchable gratings include first and second gratings disposed in a first waveguide and third and fourth gratings disposed in a second waveguide. In some embodiments, the first grating overlaps the third grating and the second grating overlaps the fourth grating. The gratings can overlap completely or partially depending on the application. In the overlapping configurations, the first and third gratings can act as input couplers, and the second and further grating can act as output couplers. FIGS. **1A-1B** conceptually illustrate side elevation views of a resolution multiplication waveguide device in accordance with an embodiment of the invention. The first configuration **100A**, which is illustrated in FIG. **1A**, is provided when the first and second switchable gratings are in their diffracting states. The second configuration **100B**, which is illustrated in FIG. **1B**, is provided when the first and second gratings are in their non-diffracting states. Referring first to FIG. **1A**, the first configuration **100A** includes an image projector **101** coupled to a resolution-multiplication waveguide that includes a first waveguide layer **102** containing a first input grating **103** and a first output grating **104**. The resolution-multiplication waveguide further includes a second waveguide layer **105** containing a second input grating **106** and a second output grating **107**. As shown, the second input grating **106** substantially overlaps the first input grating **103** and second output grating **107** substantially overlaps the first output grating **104**. Voltages can be applied to the gratings in the first waveguide layer **102** by electrical connections indicated by the symbol V and referenced by the numerals **108A-108B**.

In the illustrative embodiment of FIG. **1A**, the image projector **101** includes a microdisplay panel **101A** providing an array of pixels **101B** and a projection lens **101C** for projecting image light from the microdisplay **101A** such that light from each pixel is mapped into a unique angular direction. In some embodiments, the projection lens **101C** may be a multi-element refractive lens system. In several embodiments, the projection lens **101C** may include diffractive elements or surfaces. An image projector of this basic configuration will be assumed for the purposes of explaining the invention. However, it should be apparent to those skilled in the art that the invention may be applied using any type of image projector. In some embodiments, the image projector **101** may use a large scanner to form a pixelated image. In a number of embodiments, the image projector **101** may contain more than one microdisplay or laser scanner for providing more than one pixelated image source.

Referring again to FIG. **1A**, the device further includes an image processor **109**, which is electrically connected to the image projector **101** via a data communications and control link **109A**. The image processor **109** can be configured to compute a native (unshifted) image and at least one image shifted in a predefined direction for sequential display by the image projector **101**. Image shifts can be implemented in any of the schemes described above, including but not limited to N+ any fraction of a pixel, where N is an integer including zero. Image light from the image projector **101** can be optically coupled into the resolution multiplication waveguide by a prism **110**. In some embodiments, the prism **110** may be replaced by a grating.

When a native image frame is displayed on the microdisplay **101A**, the light path from the image projector **101**, or image generator, through the first waveguide layer **102** and into the light extraction path from the first waveguide layer **102**, with the gratings **103**, **104** of the first waveguide layer **102** in their diffracting states, is indicated in FIG. **1A** by rays **111-115** with a native image frame pixel indicated by **116**.

When a shifted image frame is displayed, the light path from the image projector **101**, or image generator, into the second waveguide layer **105** and into the light extraction path from the second waveguide layer **105** and through the first waveguide layer **102** is indicated in FIG. **1B** by rays **117-122**. The shifted image frame pixel is indicated by **123** and the corresponding native image frame pixel is again indicated by **116**. In the illustrative embodiment, zero-order light from the input gratings **103**, **106** of each of the waveguide layers **102**, **105** as indicated by ray **124** in FIG. **1A** and ray **125** in FIG. **1B** propagates substantially undeviated out of the waveguide layers **102**, **105** onto a light trap **126**. It should be apparent from the drawings that with minor modifications to the architecture shown in FIGS. **1A-1B**, either of the waveguides can be used to propagate the native image frame.

In many embodiments, the gratings of the first waveguide layer are switchable while the gratings in the second waveguide layer do not require switching. In several embodiments, the gratings in the second waveguide layer are configured to always be in their diffracting states. In some embodiments, such as the one illustrated in FIG. **2**, the gratings of both waveguide layers are switchable and configured to switch between diffracting and non-diffracting states. As shown, the configuration **200** of FIG. **2** includes a waveguide that can have similar components as shown in the embodiment of FIGS. **1A-1B**, including a first waveguide layer **201** having a first input grating **202** and a first output grating **203** and a second waveguide layer **204** having a second input grating **205** and a second output grating **206**. However, in the illustrative embodiment of FIG. **2**, the gratings **205**, **206** of the second waveguide layer **204** are switched into their non-diffracting states when the gratings **202**, **203** of the first waveguide layer **201** are switched into their diffracting states. Voltages are applied to the gratings via electrical connections to a voltage source indicated by the symbol V and referenced by the numerals **207A-207D**. By controlling the switching of the gratings **205**, **206** in the second waveguide layer **204** when the gratings **202**, **203** in the first waveguide layer **201** are diffracting, the risk of zero order light **208** coupling back into the first waveguide layer **201** can be minimized.

The gratings can be switched in coordination with the frame update of the microdisplay such that when the gratings of the first waveguide layer are in their diffracting states, the input image generator displays the native image and when the gratings of the first waveguide layer are in their non-diffracting states, the image generator displays an image recomputed with a half pixel horizontal shift. Since the switching of the native and shifted frames takes place within the human eye integration time, the display viewer can perceive a doubling of the displayed image resolution.

In many embodiments, the gratings in the first and second waveguide layers can be similarly configured but have slightly different grating prescriptions designed to produce a relative angular shift, which can be equivalent to half a pixel or any other predefined value, to the native image. In some embodiments, the required angular shift is produced by applying small tilts to the grating K-vectors. In several embodiments, the required angular shift is produced by small changes to the surface gratings formed by the input and output gratings. Since the angular separation of the native and shifted image frames is typically very small, when coupled into a display waveguide, the image light of the frames can be propagated with high efficiency before being extracted into the eye box of the waveguide display.

In some embodiments, the first and second waveguide layers are designed such that only a few total internal reflection (TIR) bounces take place before light extraction. This ensures that beam expansion is minimized for efficient coupling into a separate waveguide device.

In some embodiments, the first and second waveguide layers will be separated by a small air gap to ensure complete optical isolation. In several embodiments, a low index material such as a nanoporous material can be used for waveguide isolation.

In some embodiments, separate waveguide layers are provided for red, green, and blue light. In several embodiments, separate waveguide layers are provided for red and blue/green light. In many embodiments, the gratings multiplex more than one wavelength. In a number of embodiments, the gratings multiplex more than one angular bandwidth. In some embodiments, further resolution multiplication operations can be implemented. For example, to provide resolution quadrupling, waveguides can be further stacked to deflect light into different directions corresponding to pixel shifts in different directions. Such implementations can be based on similar principles and embodiments as those shown in FIGS. **1**A-**1**B and FIG. **2**.

In some embodiments, a resolution multiplication waveguide is optically coupled to a waveguide display. FIGS. **3**A-**3**B conceptually illustrate schematic side elevation views illustrating two operational states **300**A,**300**B of one such embodiment. As shown, the resolution multiplication waveguide, which can be implemented based on embodiments similar to those illustrated in FIGS. **1**A-**1**B and FIG. **2**, is optically coupled to a waveguide display **301**. In the illustrative embodiment, the waveguide display **301** contains an input grating **302** and an output grating **303**. In some embodiments, the waveguide display **301** may further include a fold grating. In many embodiments, the waveguide display **301** may include separate layers for propagating light of different colors. In the illustrative embodiment of FIG. **3**A, native image frame light **304** emerging from the first waveguide layer of the resolution multiplication waveguide is coupled into the waveguide display **301** along a TIR path represented by rays **305**-**306** before being coupled out of the waveguide **301** as represented by ray **307** to form an output image containing pixels such as the one indicated by **308**. As shown in FIG. **3**B, shifted image frame light **309** emerging from the second waveguide layer of the resolution multiplication waveguide is coupled into the waveguide display **301** along a TIR path represented by rays **310**-**311** before being coupled out of the waveguide as represented by ray **312** to form an output image containing pixels such as the one indicated by **313** which is shifted from the corresponding native pixel **308** by half a pixel width.

As described above, resolution multiplication applications can be implemented to provide quadrupling of the resolution of a display, that is, doubling both the vertical and horizontal resolutions. FIGS. **4**A-**4**D provide illustrations of four different pixel-shifting steps used to provide resolution quadrupling in accordance with an embodiment of the invention. FIG. **4**A shows a native image **400**A, which is represented by a 4×4 pixel array contain pixels such as **401** separated by gaps **402**. FIG. **4**B illustrates a pixel array **400**B in which each pixel, such as **403**, has undergone a first half pixel horizontal shift relative to its corresponding native pixel **401**. FIG. **4**C illustrates a pixel array **400**C in which each pixel, such as **404**, has undergone a half pixel vertical and horizontal shift relative to its corresponding native pixel **401**. FIG. **4**D illustrates a pixel array **400**D in which each pixel, such as **405**, has undergone a half pixel vertical shift relative to its corresponding native pixel **401**.

FIGS. **5**A-**5**D illustrates the grating states **500**A-**500**D of a waveguide display **501** capable of propagating the four-pixel arrays configurations illustrated in FIGS. **4**A-**4**D. As shown, the waveguide display **501** includes first and second input gratings for coupling light from an image projector **502** into a TIR path in the waveguide display **501**, The waveguide display **501** further includes first and second output gratings for coupling light out of the waveguide display **501**. Although the waveguide display **501** is illustrated as a single layer, such waveguide displays can be implemented with multiple waveguide layers, each containing a grating layer. Referring back to FIG. **5**A, the waveguide display **501** further includes a common fold grating **503** disposed in the same grating layer as first input and output gratings, which can be used in both grating configurations **500**A, **500**B to provide two-dimensional beam expansion in association with the first and second output gratings. The fold grating **503** may be disposed in either of the two grating layers. In some embodiments, the fold grating **503** may not be required. Voltages are applied to the gratings via electrical connections to a voltage source indicated by the symbol V and referenced by the numerals **504**A-**504**D.

FIG. **5**A illustrates the grating configuration **500**A for propagating the pixel configuration of FIG. **4**A (native image) in which the second input grating and the second output grating are in their diffracting states **505**A, **506**A respectively and the first input grating and the first output grating are in their non-diffracting states **507**B, **508**B respectively. The ray path is indicated by rays **509**A-**512**A. FIG. **5**B illustrates the grating configuration **500**B for propagating the pixel configuration of FIG. **4**B in which the first input grating and the second output grating are in their diffracting states **507**A,**506**A respectively and the second input grating and the first output grating are in their non-diffracting states **505**B, **508**B respectively. The ray path is indicated by rays **509**B-**512**B. FIG. **5**C illustrates the grating configuration **500**C for propagating the pixel configuration of FIG. **4**C in which the first input grating and the first output grating are in their diffracting states **507**A, **508**A respectively and the second input grating and the second output grating are in their non-diffracting states **505**B, **506**B respectively. The ray path is indicated by rays **509**C-**512**C. FIG. **5**D illustrates the grating configuration **500**D for propagating the pixel configuration of FIG. **4**D in which the second input grating and the first output grating are in their diffracting states **505**A, **508**A respectively and the first input grating and the second output grating are in their non-diffracting states **507**BA, **506**B respectively. The diffracted ray path is indicated by the rays **510**D-**513**D.

Achieving a 60 Hz 1080p image frame rate using the apparatus of FIGS. **5**A-**5**D can require four video sub-frames to be generated at 240 Hz video frame rate. Each video sub-frame can require red, green, blue sub-frames, increasing the frame rate to 720 Hz. In some embodiments, the two-layer grating architecture illustrated in FIGS. **5**A-**5**D is used to propagate monochromatic light with further similar waveguides being required for other colors. For example, in some embodiments, separate waveguides would be required for red, green, and blue. In several embodiments, color display is provided with one red waveguide and one blue/green waveguide. The switchable grating arrangement of FIGS. **5**A-**5**D has several advantages including but not limited to: low cost and complexity; the input image from the projector passing through the minimum number of ITO layers; and the dual switchable grating offsets being switched separately thereby minimizing loss.

It should be apparent from consideration of FIGS. **5**A-**5**D, in some embodiments, one of the first or second input gratings may be eliminated to provide a waveguide that propagates the native image and a shifted image sequentially. Alternatively, by the same reasoning, one of the first or second output gratings may be eliminated to achieve the same effect. In some embodiments, one of the grating layers in FIGS. **5**A-**5**D may be non-switching.

FIG. **6** is a flow diagram conceptually illustrating a method **600** of multiplying the resolution of a waveguide display in accordance with an embodiment of the invention. Referring to the flow diagram, the method **600** includes providing (**601**) an image projector and an image processor and providing (**602**) a waveguide containing first, second, third, and fourth switchable gratings with first and third gratings overlapping and the second and fourth gratings overlapping and each grating having an optical prescription for applying an angular shift to incident light. A pixel shift (N+½) multiplied by P can be performed (**603**), where N is an integer greater than or equal to zero and P is a pixel dimension. As described above, any fractional pixel shift can be implemented instead of ½. A shifted image can be computed (**604**) using the image processor. A shifted image can be written (**605**) to the image projector. One of the first and third switchable gratings and one of the second and fourth switchable gratings can be switched (**606**) into their diffracting states. Shifted image light can be coupled (**607**) into the waveguide via the diffracting first or third switchable gratings. Image light can be coupled (**608**) out of the waveguide via the diffracting second or fourth switchable gratings with a pixel shift determined by the prescriptions of the diffracting switchable gratings. The pixel shift step can be repeated (**608**) until all required image pixel shifts have been completed.

In addition to resolution multiplication waveguide architectures, waveguides for multiplying resolution and field-of-view can also be implemented using related principles similar to those shown in FIGS. **1**-**6**. FIG. **7** is a schematic illustration of an apparatus for multiplying the resolution and field-of-view in accordance with an embodiment of the invention. As shown, the apparatus **700** includes a first waveguide **701** for multiplying resolution (which can be implemented in accordance with any of the above described embodiments), an input image source **702** provide image modulated light **703**, a second waveguide **704** for multiplying field-of-view supporting input gratings **705**A,**705**B and output gratings **706**A,**706**B. The first waveguide **701** provides resolution multiplied light **707**A, which is coupled into the second waveguide **704**. In some embodiments, the input gratings **705**A, **705**B are switchable gratings and the output gratings **706**A, **706**B are non-switching gratings. In many embodiments, the one of the input gratings **705**A, **705**B can be non-switching gratings and one or both of the output gratings can be non-switching gratings. In several embodiments, all of the gratings can be switching.

In the embodiments of FIG. **7**, the input grating **705**A and the output grating **706**A provide a first waveguide path for a first field-of-view portion. The first waveguide path is illustrated by the total internal reflection rays **707**B,**707**C which are coupled out of the waveguide **704** by the output grating **706**A into a ray path **707**D to the eyebox **708**. The input grating **705**B and the output grating **706**B can provide a second waveguide path (not shown) for a second field-of-view portion. In many embodiments, the image source **702** provides first image modulated light for projection into the first field-of-view portion when the input grating **705**A and the output grating **706**A are in their diffracting states and the input grating **705**B and the output grating **706**B are in their non-diffracting states. In some embodiments, the image source provides second image modulated light for projection into the second field-of-view portion when the input grating **705**A and the output grating **706**A are in their non-diffracting states and the input grating **705**B and the output grating **706**B are in their diffracting states. As can be readily appreciated, various diffracting and non-diffracting configurations can be implemented for propagating the first and second image modulated light. From consideration of FIG. **7**, it should be apparent that further input and output gratings can be added for the purposes of producing further field-of-view portions for viewing. In many embodiments, multiple fields of view portions can be tiled to provide a continuous and expanded field-of-view. In some embodiments, field-of-view portions do not need to abut.

FIG. **8** conceptually illustrates a waveguide **800** showing how in-coupling switchable diffractive elements and out-coupling diffractive elements can be paired up and switched in and out (on and off or vice versa) so that the output light does not suffer from image doubling and chromatic aberration, which could be present if non-switchable diffraction elements are utilized as discussed earlier. As shown, waveguide **800** includes input diffractive elements **801**-**803** (or input gratings) and output diffractive elements **804**-**806** (or output gratings). In some embodiments, the input diffractive elements **801**-**803** are switchable gratings and the output diffractive elements **804**-**806** are non-switching gratings. In many embodiments, the input diffractive elements **801**-**803** and the output diffractive elements **804**-**806** can include any combination of switching and non-switching gratings. In several embodiments, all of the diffractive elements can be switching. The diffractive elements can be formed in one or more layers of holographic recording medium. In the illustrative embodiment, the diffractive elements are formed in a holographic recording medium **807** sandwiched by substrates **808**A, **808**B. In other embodiments, each input diffractive element and its corresponding output diffractive element are formed in a holographic recording medium sandwiched by two transparent substrates. In several embodiments, the input diffractive elements **801**-**803** and corresponding output diffractive elements **804**-**806** have equal and opposite diffractive power. In the illustrative embodiment, input light is received from three different angles. The three angles can each correspond to the principal or center angles of incident rays contained within a portion of a field-of-view. In some embodiments, an input collimating lens (which is not illustrated) generates a field-of-view that is needed for the optical display system. According to some exemplary embodiments, the collimating lens may be integrated with the input diffractive elements, while in other exemplary embodiments, the collimating lens may be separate. At any point in time, only one of each input element **801**, **802**, **803** may be operational or switched on along with its corresponding output element **804**, **805**, **806** respectively and all elements may switch consecutively within the frame time of the system. In several embodiments, light does not couple into waveguide **800** until it hits a diffractive element (**801**, **802**, or **803**) that is operational. Therefore, only light from one angle range is coupled into waveguide at any one point in time. Further, in such embodiments, light does not couple out of the substrate until it hits the diffraction element (**804**, **805**, or **806**) that is operational. In some embodiments, using non-switching gratings for an input or output grating can result in incident light rays being off-Bragg (that is, not satisfying the Bragg equation) for a particular grating.

According to the illustrated example, a single parallel beam of light shown by dashed lines hits diffraction surface and is diffracted into waveguide until it hits complimentary diffractive surface and is diffracted out of waveguide at the same angle as it enters waveguide. Ray paths are indicated by rays **809**A-**809**C. Because the input diffractive power is equal and opposite to the output diffractive power no chromatic aberration is induced in the system. It is noted that while FIG. **8** illustrates use of three input and output switchable diffractive elements, according to other exemplary embodiments, more or fewer than three switchable diffractive elements may be used. It is also noted that while the FIG. **8** illustrates reception and output of light at three different angles, the figure does not include the light in the range between the three field angles shown. The light incident on each of the diffractive surfaces are in a range limited by the diffraction efficiency angular bandwidths of the gratings.

While the waveguide of FIG. **8** has been illustrated as having single rows of diffractive elements, according to other exemplary embodiments, a waveguide can include in-coupling and out coupling gratings disposed in two dimensional arrays with correspond input and output elements paired up according to the principles illustrated in FIG. **8** with corresponding elements of the input and output arrays having equal and opposite grating vector components.

In some embodiments, the field-of-view multiplication waveguide can further include fold grating(s) for providing a first beam expansion with the output grating(s) providing a second expansion orthogonal to the first beam expansion. In such configurations, the input, output, and fold gratings can have gratings vectors summing to substantially zero. In some embodiments, the field-of-view multiplication waveguide support gratings for diffracting different wavelength bands. In several embodiments, the field-of-view multiplication waveguide support gratings for diffracting different incident light polarizations. In a number of embodiments, the field-of-view multiplication waveguide support can support at least one multiplexed grating for diffracting light of different wavelength bands, angular bandwidths, or polarization states. In many embodiments, the field-of-view multiplication waveguide can support at least one rolled k-vector grating. In some embodiments, the field-of-view multiplication waveguide can support at least one dual interaction grating.

FIG. **9** conceptually illustrates a waveguide for multiplying the resolution and field-of-view in accordance with an embodiment of the invention. The apparatus **900** includes a waveguide **901** supporting a first pair of input gratings **902**A,**902**B, a second pair of input gratings **903**A,**903**B and a first pair of output gratings **902**C,**902**D and a second pair of output gratings **903**C,**903**D. In the illustrative embodiment, the first pair of input gratings **902**A,**902**B and the first pair of output gratings **902**C,**902**D provide resolution multiplication for light to be projected in a first field-of-view portion with the gratings being switched to provide waveguide paths for native image and pixel shifted images according to the principles discussed in the preceding sections (such as those illustrated in FIGS. **1**-**6**). Ray paths from the image source **904** to the eye box **905** are represented by the rays **906**-**908**. The second pair of input gratings **903**A, **903**B and the second pair of output gratings **903**C,**903**D provide resolution multiplication for light to be projected in a second field-of-view portion with the gratings being switched to provide waveguide paths for native image and pixel shifted images. Providing the first and second field-of-view portion can be implemented in accordance with any of the principles described in the sections above. As can readily be appreciated, the input and output gratings can be disposed across several grating layers and/or waveguides that can be stacked to implement similar functions.

FIG. **10** is a flow diagram conceptually illustrating a method of multiplying the field-of-view and resolution of an image in accordance with an embodiment of the invention. As shown, the method **1000** of multiplying the field-of-view and resolution of an image is provided. Referring to the flow diagram, the method **1000** includes providing (**1001**) an image projector for directing light from pixels of a pixelated image display into unique angular directions, providing (**1002**) an image processor for computing native images corresponding to first and second field-of-view portions, at least one first field-of-view image shifted in a predefined direction and at least one second field-of-view image shifted in a predefined direction, providing (**1003**) a first waveguide supporting input gratings and output gratings for multiplying image resolution in at least one of two orthogonal directions, and providing (**1004**) a second waveguide supporting input gratings and output gratings for providing a first waveguide path for a first field-of-view portion and a second waveguide path for a second field-of-view portion. In some embodiments, the input gratings are switchable gratings and the output grating are non-switching gratings. In many embodiments, at least one of the input gratings can be non-switching gratings and at least one of the output gratings can be non-switching gratings. In several embodiments, all of the gratings can be switching.

Referring again to FIG. **10**, the method **1000** further includes computing (**1005**) a first image for projection into a first field-of-view. The resolution of the first field-of-view image can be multiplied (**1006**) using the first waveguide. The input grating and the output grating for propagating light for projection into the first field-of-view portion can be switched (**1007**) into their diffracting states at the same time as the input grating and output grating for propagating light for projection into the second field-of-view portion are switched into their non-diffracting states. The resolution multiplied first field-of-view portion can be projected (**1008**) for viewing. A second image for projection into the second field-of-view can be computed (**1009**) using the image processor. The resolution of the second field-of-view image can be multiplied (**1010**) using the first waveguide. The input grating and the output grating for propagating light for projection into the first field-of-view portion can be switched (**1011**) into their non-diffracting states at the same time as the input grating and output grating for propagating light for projection into the second field-of-view portion are switched into their diffracting states. The resolution multiplied second field-of-view portion can be projected (**1012**) for viewing.

Although FIGS. **7**-**10** illustrate specific configurations and methods, it should be readily apparent that various components and steps can be modified, removed, or included depending on the specific requirements of a given application. For example, FIG. **10** describe a method for multiplying the field-of-view and resolution using two separate waveguides. In other embodiments, the functions of the two waveguides can be implemented in a single waveguide.

Other Embodiments

The embodiments and techniques described in the sections above can be configured and modified in many different ways. For example, devices in accordance with various embodiments of the invention can incorporate the techniques and teachings disclosed in the U.S. patent application Ser. No. 16/162,280 filed Oct. 16, 2018, entitled "Systems and Methods for Multiplying the Resolution of a Pixelated Display;" U.S. Pat. No. 8,817,350 filed Jan. 20, 2012, entitled "Optical Displays;" and U.S. patent application Ser.

No. 13/869,866 filed Apr. 24, 2013, entitled "Holographic Wide Angle Display," the disclosures of which are hereby incorporated by reference in their entireties for all purposes. Furthermore, waveguide embodiments can include various grating configurations. In some embodiments, the switchable gratings are disposed in a waveguide further including a non-switching grating. In some embodiments, the non-switching grating is a fold grating (sometimes referred to as a turning grating) used for beam expansion as described in the references. In such embodiments, the invention provides a displays waveguide embodying resolution multiplication and two-axis beam expansion. In some embodiments, at least one of the gratings used for resolution multiplication is a rolled k-vector grating. The K-vector (more commonly referred to as the grating vector) is a vector-aligned normal to the grating planes (or fringes) which determines the optical efficiency for a given range of input and diffracted angles. Rolling the K-vectors allows the angular bandwidth of the grating to be expanded without the need to increase the waveguide thickness. In some embodiments, the switchable gratings include at least one grating multiplexing at least one of wavelength or angular bandwidth. It is well established in the literature of holography that more than one holographic prescription can be recorded into a single holographic layer. Methods for recording such multiplexed holograms are well known to those skilled in the art. In some embodiments, at least one of the switching gratings and other gratings used in association with them may combine two or more angular diffraction prescriptions to expand the angular bandwidth or to expand the spectral bandwidth. For example, color multiplexed gratings may be used to diffract two or more of the primary colors.

In any of the above described embodiments the image projector, which is referred to in some of the references an Input Image Node (IIN), may integrate a microdisplay panel, light source and other optical components commonly used to illuminate the display panel, separate the reflected light and collimate it into the required field-of-view. In some embodiments, the image projector may be based on the embodiments and teachings disclosed in U.S. patent application Ser. No. 13/869,866 entitled HOLOGRAPHIC WIDE-ANGLE DISPLAY, and U.S. patent application Ser. No. 13/844,456 entitled TRANSPARENT WAVEGUIDE DISPLAY. In some embodiments, the image projector contains a beamsplitter for directing light onto the microdisplay and transmitting the reflected light towards the waveguide. In some embodiments, the beamsplitter is a grating recorded in HPDLC and uses the intrinsic polarization selectivity of such gratings to separate the light illuminating the display and the image modulated light reflected off the display. In some embodiments, the beam splitter is a polarizing beam splitter cube. In some embodiment, the image projector incorporates an illumination homogenizer or a laser beam despeckler. Advantageously, the despeckler is holographic waveguide device based on the embodiments and teachings of U.S. Pat. No. 8,565,560 entitled LASER ILLUMINATION DEVICE.

In some embodiments, the light source is a laser. In some embodiments, the light source is a LED. In some embodiments, the image projector includes one or more lenses for modifying the illumination angular characteristics. LED will provide better uniformity than laser. If laser illumination is used, there is a risk of illumination banding occurring at the waveguide output. In some embodiments laser illumination banding in waveguides can be overcome using the techniques and teachings disclosed in U.S. patent application Ser. No. 15/512,500 entitled METHOD AND APPARATUS FOR GENERATING INPUT IMAGES FOR HOLOGRAPHIC WAVEGUIDE DISPLAYS. In some embodiments, the light from the light source is polarized. In one or more embodiments, the image source is a liquid crystal display (LCD) micro display or liquid crystal on silicon (LCoS) micro display. In some embodiments, the image source is a MEMs device. In some embodiments, the image source is a display panel based on Texas Instruments' Digital Light Projector (DLP) technology.

In some embodiments, any of the gratings used to apply the invention may encoded optical power for adjusting the collimation of the output. In some embodiments, the output image is at infinity. In some embodiments, the output image may be formed at distances of several meters from the waveguide.

In some embodiments using fold gratings, the fold grating angular bandwidth is enhanced by designing the grating prescription provides dual interaction of the guided light with the grating. Exemplary embodiments of dual interaction fold gratings are disclosed in U.S. patent application Ser. No. 14/620,969 entitled WAVEGUIDE GRATING DEVICE.

In some embodiments, the waveguides used in the invention are formed by sandwiching the grating layers between glass or plastic substrates to form a stack within which total internal reflection occurs at the outer substrate and air interfaces. The stack may further comprise additional layers such as beam splitting coatings and environmental protection layers. In some embodiments, the cell substrates may be fabricated from glass. An exemplary glass substrate is standard Corning Willow glass substrate (index 1.51) which is available in thicknesses down to 50 microns. In other embodiments, the cell substrates may be optical plastics. In some embodiments, the gratings may be recorded in layers of material coated onto a transparent substrate and covered by a protective transparent layer after the holographic exposure process has been completed. In some embodiments, the grating layer may be broken up into separate layers. For example, in some embodiments, a first layer includes the fold grating while a second layer includes the output grating. In some embodiments, a third layer can include the input coupler or grating. The number of layers may then be laminated together into a single waveguide substrate. In some embodiments, the grating layer is comprised of a number of pieces including the input coupler, the fold grating and the output grating (or portions thereof) that are laminated together to form a single substrate waveguide. The pieces may be separated by optical glue or other transparent material of refractive index matching that of the pieces. In another embodiment, the grating layer may be formed via a cell making process by creating cells of the desired grating thickness and vacuum filling each cell with holographic recording material for each of the input coupler, the fold grating and the output grating. In one embodiment, the cell is formed by positioning multiple plates of glass with gaps between the plates of glass that define the desired grating thickness for the input coupler, the fold grating and the output grating. In one embodiment, one cell may be made with multiple apertures such that the separate apertures are filled with different pockets of holographic recording material. Any intervening spaces may then be separated by a separating material such as glue or oil to define separate areas. In one embodiment, the holographic material may be spin-coated onto a substrate and then covered by a second substrate after curing of the material. By using the fold grating, the waveguide display advantageously requires fewer layers than previous systems and methods of displaying information according to some embodiments. In addition, by using fold grating, light can travel by total internal refection within the waveguide in a single rectangular prism defined by the waveguide outer surfaces while achieving dual pupil expansion. In another embodiment, the input coupler, the fold grating, and the output grating can be created by interfering two waves of light at an angle within the substrate to create a holographic wave front, thereby creating light and dark fringes that are set in the waveguide substrate at a desired angle. In some embodiments, the grating in a given layer is recorded in stepwise fashion by scanning or stepping the recording laser beams across the grating area. In some embodiments, the gratings are recorded using mastering and contact copying process currently used in the holographic printing industry.

In some embodiments, the gratings are recorded in a holographic polymer dispersed liquid crystal (HPDLC) (e.g., a matrix of liquid crystal droplets), although SBGs may also be recorded in other materials. In one embodiment, SBGs are recorded in a uniform modulation material, such as POLICRYPS or POLIPHEM having a matrix of solid liquid crystals dispersed in a liquid polymer. The SBGs can be switching or non-switching in nature. In its non-switching form, an SBG has the advantage over conventional holographic photopolymer materials of being capable of providing high refractive index modulation due to its liquid crystal component. Exemplary uniform modulation liquid crystal-polymer material systems are disclosed in United State Patent Application Publication No.: US2007/0019152 by Caputo et al and PCT Application No.: PCT/EP2005/006950 by Stumpe et al. both of which are incorporated herein by reference in their entireties. Uniform modulation gratings are characterized by high refractive index modulation (and hence high diffraction efficiency) and low scatter.

In some embodiments, at least one of the gratings is recorded a reverse mode HPDLC material. Reverse mode HPDLC differs from conventional HPDLC in that the grating is passive when no electric field is applied and becomes diffractive in the presence of an electric field. The reverse mode HPDLC may be based on any of the recipes and processes disclosed in PCT Application No.: PCT/GB2012/000680, entitled IMPROVEMENTS TO HOLOGRAPHIC POLYMER DISPERSED LIQUID CRYSTAL MATERIALS AND DEVICES. The grating may be recorded in any of the above material systems but used in a passive (non-switching) mode. The fabrication process is identical to that used for switched but with the electrode coating stage being omitted. LC polymer material systems are highly desirable in view of their high index modulation. In some embodiments, the gratings are recorded in HPDLC but are not switched.

In some embodiments of the invention, the resolution multiplication apparatus is used in an eye tracked display comprising a waveguide display according to the principles of the invention and an eye tracker. In one preferred embodiment, the eye tracker is a waveguide device based on the embodiments and teachings of PCT/GB2014/000197 entitled HOLOGRAPHIC WAVEGUIDE EYE TRACKER, PCT/GB2015/000274 entitled HOLOGRAPHIC WAVEGUIDE OPTICAL TRACKER, and PCT Application No. GB2013/000210 entitled APPARATUS FOR EYE TRACKING.

In some embodiments of the invention, the resolution multiplication apparatus is used in a waveguide display further comprises a dynamic focusing element. The dynamic focusing element may be based on the embodiments and teachings of U.S. Provisional Patent Application No. 62/176,572 entitled ELECTRICALLY FOCUS TUNABLE LENS. In some embodiments, a dual expansion waveguide display further comprising a dynamic focusing element and an eye tracker may provide a light field display based on the embodiments and teachings disclosed in U.S. Provisional Patent Application No. 62/125,089 entitled HOLOGRAPHIC WAVEGUIDE LIGHT FIELD DISPLAYS.

In some embodiments, a resolution multiplication apparatus according to the principles of the invention may be used in a waveguide display integrated within a window, for example, a windscreen-integrated HUD for road vehicle applications. In some embodiments, a window-integrated display may be based on the embodiments and teachings disclosed in U.S. Provisional Patent Application No. 62/125,064 entitled OPTICAL WAVEGUIDE DISPLAYS FOR INTEGRATION IN WINDOWS and U.S. Provisional Patent Application No. 62/125,066 entitled OPTICAL WAVEGUIDE DISPLAYS FOR INTEGRATION IN WINDOWS. In some embodiments, the resolution multiplication apparatus may include gradient index (GRIN) wave-guiding components for relaying image content between the image projector and the waveguide containing the resolution multiplication gratings. Exemplary embodiments are disclosed in U.S. Provisional Patent Application No. 62/123,282 entitled NEAR EYE DISPLAY USING GRADIENT INDEX OPTICS and U.S. Provisional Patent Application No. 62/124,550 entitled WAVEGUIDE DISPLAY USING GRADIENT INDEX OPTICS. In some embodiments, a resolution multiplication apparatus may be used in a dual expansion waveguide display incorporating a light pipe for providing beam expansion in one direction based on the embodiments disclosed in U.S. Provisional Patent Application No. 62/177,494 entitled WAVEGUIDE DEVICE INCORPORATING A LIGHT PIPE. In some embodiments, the input image source in the image projector may be a laser scanner as disclosed in U.S. Pat. No. 9,075,184 entitled COMPACT EDGE ILLUMINATED DIFFRACTIVE DISPLAY.

The embodiments of the invention may be used in wide range of displays including HMDs for AR and VR, helmet mounted displays, projection displays, heads up displays (HUDs), Heads Down Displays, (HDDs), autostereoscopic displays and other 3D displays. In some embodiments, a resolution multiplication apparatus according to the principles of the invention may be interfaced to an Augmented Reality (AR) waveguide display with a field-of-view of 50 degrees diagonal. Examples of waveguide displays that can be used in applications of the present invention are discussed in the reference documents. Applications of the invention are not necessarily confined to waveguide displays. In some embodiments, the resolution doubling waveguide may provide a compact image generator for use in any type of wearable or projection display. In some embodiments, the resolution multiplication apparatus may provide an image projector. In some embodiments, the apparatus is optically coupled to one of image display optics, an eyepiece, a projection lens, or a waveguide. In some embodiments, the apparatus forms part of a HMD, a HUD, an eye-slaved display, a dynamic focus display or a light field display. Some of the embodiments and teachings of this disclosure may be applied in waveguide sensors such as, for example, eye trackers, fingerprint scanners and LIDAR systems.

It should be emphasized that the drawings are exemplary and that the dimensions have been exaggerated. For example, thicknesses of the SBG layers have been greatly exaggerated. Optical devices based on any of the above-described embodiments may be implemented using plastic substrates using the materials and processes disclosed in PCT Application No.: PCT/GB2012/000680, entitled IMPROVEMENTS TO HOLOGRAPHIC POLYMER DISPERSED LIQUID CRYSTAL MATERIALS AND DEVICES. In some embodiments, the waveguide embodiments of the invention may be curved.

The construction and arrangement of the systems and methods as shown in the various exemplary embodiments are illustrative only. Although only a few embodiments have been described in detail in this disclosure, many modifications are possible (for example, variations in sizes, dimensions, structures, shapes and proportions of the various elements, values of parameters, mounting arrangements, use of materials, colors, orientations, etc.). For example, the position of elements may be reversed or otherwise varied and the nature or number of discrete elements or positions may be altered or varied. Accordingly, all such modifications are intended to be included within the scope of the present disclosure. The order or sequence of any process or method steps may be varied or re-sequenced according to alternative embodiments. Other substitutions, modifications, changes, and omissions may be made in the design, operating conditions, and arrangement of the exemplary embodiments without departing from the scope of the present disclosure.

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While the above description contains many specific embodiments of the invention, these should not be construed as limitations on the scope of the invention, but rather as an example of one embodiment thereof. It is therefore to be understood that the present invention may be practiced in ways other than specifically described, without departing from the scope and spirit of the present invention. Thus, embodiments of the present invention should be considered in all respects as illustrative and not restrictive. Accordingly, the scope of the invention should be determined not by the embodiments illustrated, but by the appended claims and their equivalents.

What is claimed is:

1. An apparatus for multiplying display resolution and field-of-view, the apparatus comprising:

an image projector for directing light from a plurality of pixels of a pixelated image source into unique angular directions wherein the image projector comprises a microdisplay panel optically connected to a projection lens;

an image processor electrically connected to the image projector for computing native images of the image source corresponding to first and second field-of-view portions and for computing shifted images in a predefined direction corresponding to the first and second field-of-view portions for sequential display by the image projector;

a first set of gratings comprising a first input grating optically coupled to the image projector and a first output grating, wherein the first set of gratings comprises at least one switchable grating switchable between a diffracting state and a non-diffracting state, wherein the first set of gratings have a native configuration for propagating the light of the native image and at least one shifted configuration for propagating the light of at least one shifted image, each with an angular displacement corresponding to an image shift in the predefined direction, where the image shift is equal to N+1/M times a pixel dimension, where N and M are integers and N includes zero; and

a second set of gratings comprising a second input grating optically coupled to the first output grating of the first set of gratings, wherein the second set of gratings comprises at least one switchable grating switchable between a diffracting state and a non-diffracting state, wherein the second set of gratings have a first configuration for projecting the first field-of-view portion and a second configuration for projecting the second field-of-view portion.

2. The apparatus of claim **1**, wherein the first set of gratings is disposed in a first waveguide and the second set of gratings is disposed in a second waveguide.

3. The apparatus of claim **1**, wherein the second set of gratings comprises first, second, third, and fourth gratings, wherein the first grating overlaps the third grating and the second grating overlaps the fourth grating, and wherein the first and third gratings act as input couplers and the second and fourth gratings act as output couplers.

4. The apparatus of claim **3**, wherein at least one of the first and third gratings is a switchable grating.

5. The apparatus of claim **4**, wherein the first, second, third, and fourth gratings are switchable gratings, wherein the first configuration for projecting the first field-of-view portion is provided by one of the first or third switchable gratings and one of the second or fourth switchable gratings in their diffracting states.

6. The apparatus of claim **3**, wherein the second and fourth gratings are non-switchable gratings.

7. The apparatus of claim **3**, wherein the first and second switchable gratings are disposed in a first layer within a waveguide and the third and fourth switchable gratings are disposed in a second layer within the waveguide.

8. The apparatus of claim **3**, wherein the first and second switchable gratings are disposed in a first waveguide and the third and fourth switchable gratings are disposed in a second waveguide.

9. The apparatus of claim **1**, wherein M is equal to 2.

10. The apparatus of claim **1**, wherein the native and the at least one shifted image are sequentially displayed within a human eye integration period.

11. The apparatus of claim **1**, wherein the image shift comprises one of vertical or horizontal shifts.

12. The apparatus of claim **1**, wherein the image shift comprises vertical and horizontal shifts.

13. The apparatus of claim **1**, wherein the switchable gratings are recorded in a holographic polymer dispersed liquid crystal material.

14. The apparatus of claim **1**, wherein the second set of gratings comprises a non-switchable grating.

15. The apparatus of claim **1**, wherein the second set of gratings comprises a fold grating.

16. The apparatus of claim **1** wherein the second set of gratings comprises at least one grating multiplexing at least one of wavelength or angular bandwidth.

17. The apparatus of claim **1**, wherein the image projector is optically coupled to the first input grating of the first set of gratings by one of a prism or grating.

18. The apparatus of claim **1**, further comprising an illumination homogenizer.

19. The apparatus of claim **1** wherein the second set of gratings comprises a rolled k-vector grating.

20. A method of multiplying the resolution and field-of-view of a waveguide display, the method comprising:

providing an image projector and an image processor;

providing a waveguide display comprising first and second sets of gratings, wherein each of the first and second sets of gratings comprises at least one switchable grating switchable between a diffracting state and a non-diffracting state, wherein the first set of gratings has a native switching configuration and a shifted switching configuration, wherein the second set of grating has a first switching configuration and a second switching configuration; and

sequentially projecting at least four images, wherein the at least four images comprise a native image in a first field-of-view portion, a shifted image in a first field-of-view portion, a native image in a second field-of-view portion, and a shifted image in a second field-of-view portion, wherein the shifted image has an angular displacement with respect to a corresponding native image defined as an image shift that is equal to N+1/M times a pixel dimension, where N and M are integers and N includes zero;

wherein:

the native image in the first field-of-view portion is projected when the first set of gratings is in the native switching configuration and the second set of gratings is in the first switching configuration;

the native image in the second field-of-view portion is projected when the first set of gratings is in the native switching configuration and the second set of gratings is in the second switching configuration;

the shifted image in the first field-of-view portion is projected when the first set of gratings is in the shifted switching configuration and the second set of gratings is in the first switching configuration; and

the shifted image in the second field-of-view portion is projected when the first set of gratings is in the shifted switching configuration and the second set of gratings is in the second switching configuration.

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